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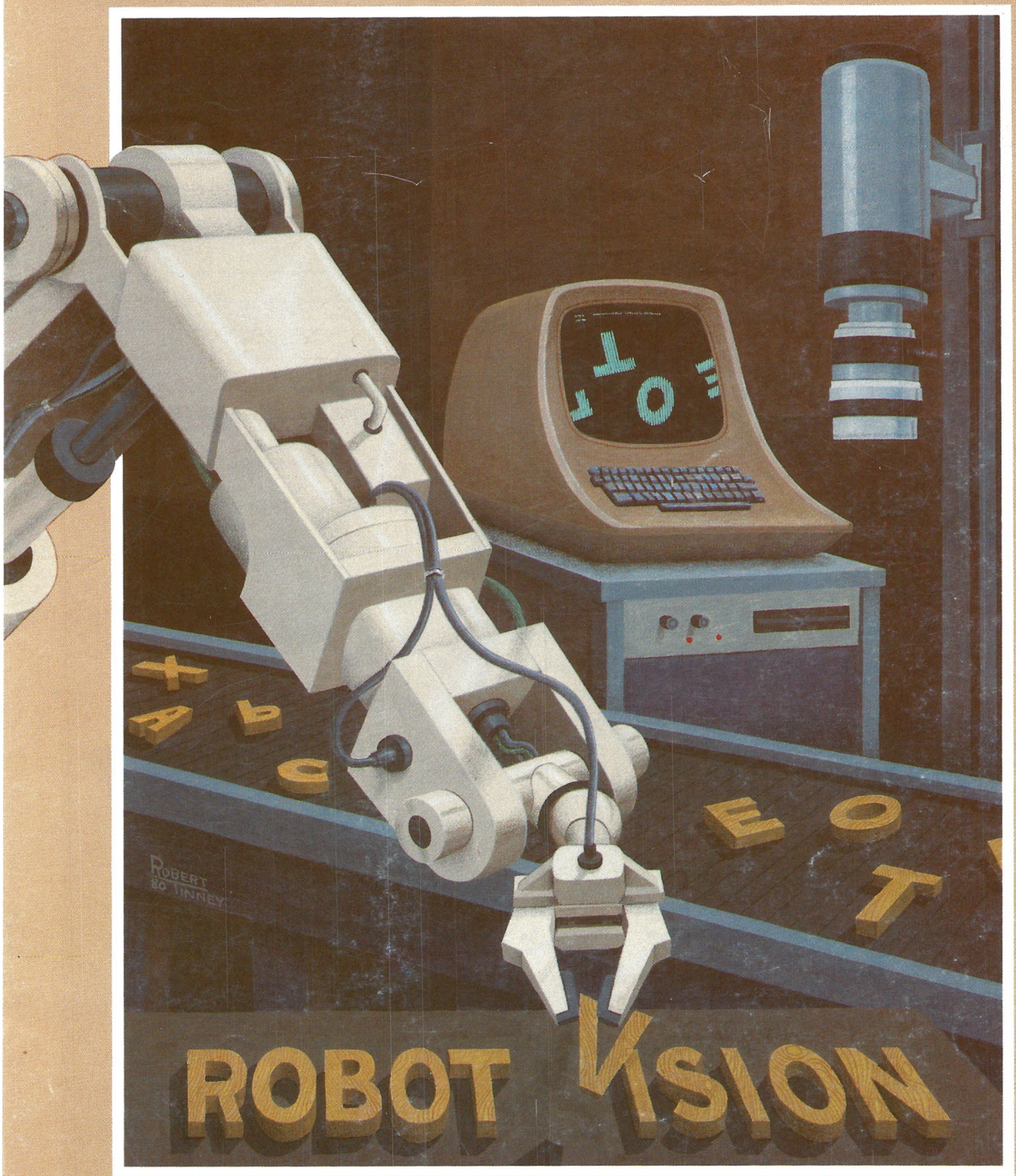

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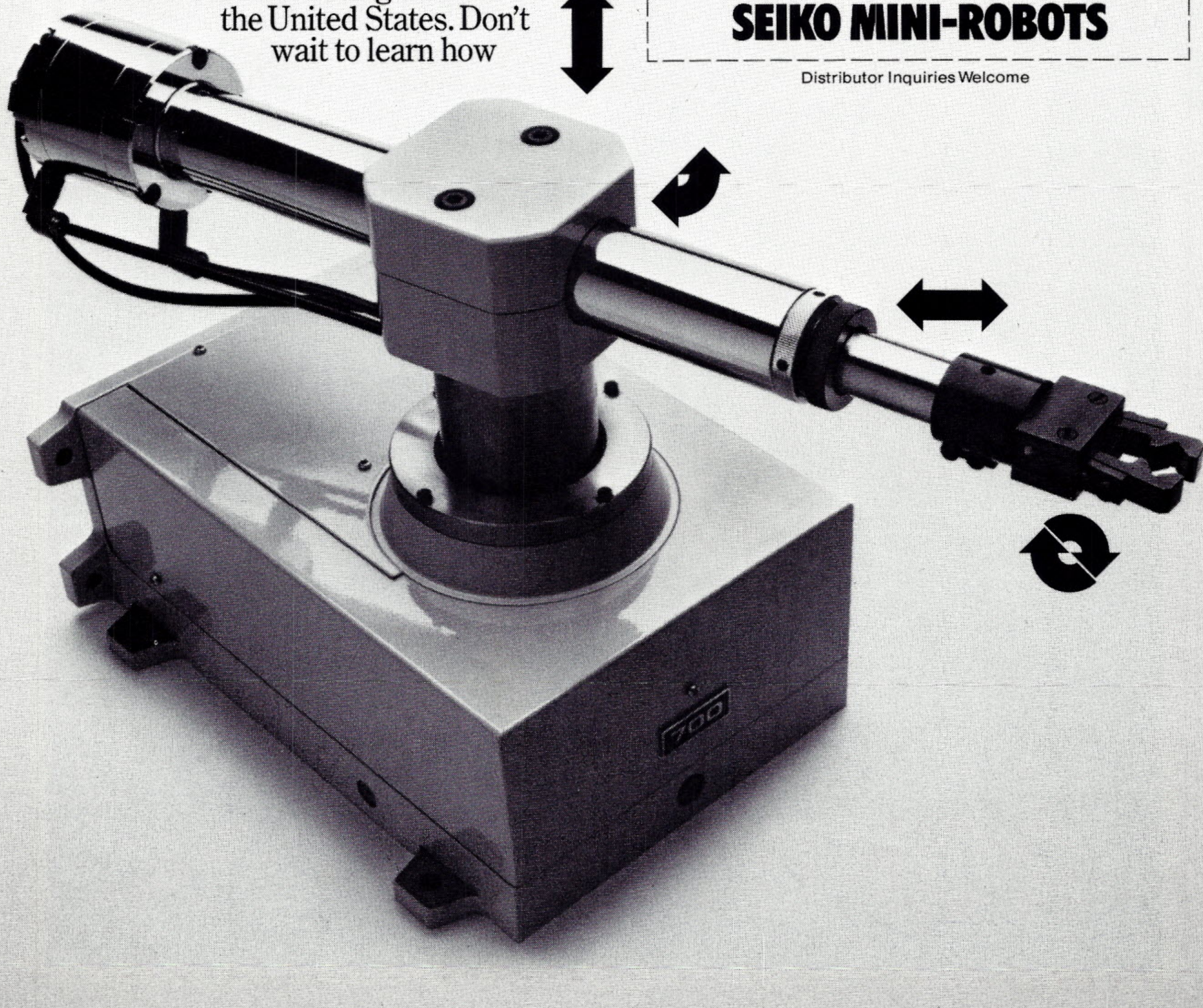

Bruce McDonald

ROBOTICS AGE

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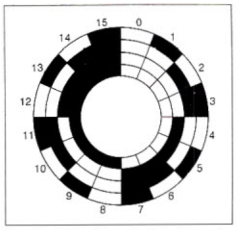

Figure 1. An absolute shaft encoder utilizing a binary code.

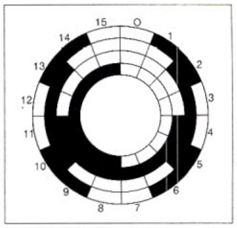

Figure 2. An absolute shaft encoder utilizing a grey code.

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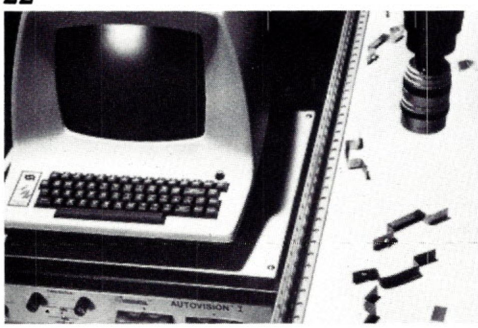

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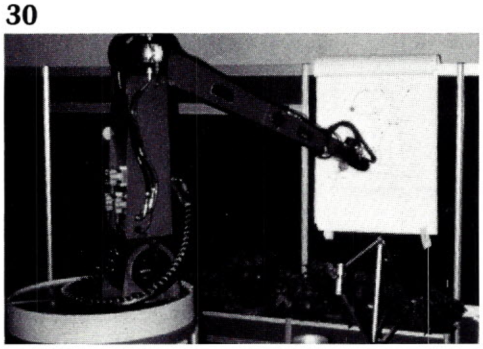

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USING OPTICAL SHAFT ENCODERS

by

Wesley E. Snyder
and
Jorg Schött

Control of a robot requires knowledge of the position and velocity of each joint. There are a number of ways to get this information. Among the more recent and more accurate techniques are those which involve a particular kind of transducer, a calibrated rotary shaft called an *optical shaft encoder*, and special purpose hardware to interface the encoder to the computer.

We will describe the two major types of optical shaft encoders and present a design for a system which will translate pulses from one of these to position increment signals which may be processed by a simple counter circuit for use by a microprocessor, in this case a TI 9900.

The cost of building and maintaining solid-state hardware depends to a large extent on the number of interconnections between chips which are required. Therefore, our design has been optimized to reduce the number of chips rather than according to some other optimizing factor such as the total number of gates. Also, since most engineers can seldom resist the temptation to innovate and improve on "canned" designs, we discuss a few of the crucial design considerations and caveats.

Optical Shaft Encoders

There are two basic types of optical shaft encoders, absolute and incremental. In our design we chose the incremental shaft encoder because it can provide a high degree of resolution at a relatively low cost. However, in some applications the absolute optical shaft encoder is easier to use and can avoid certain problems in information transmission, which we shall explain.

Absolute Optical Shaft Encoders

This type of encoder consists of a circular glass disc imprinted with rows of broken concentric arcs. A light source is assigned to each row with a corresponding detector on the opposite side of the disc. The arcs and sensors are arranged so that, as the light shines through the disc, the position of the shaft can be uniquely identified by the pattern of activated sensors (to within a given angular resolution).

The pattern of activated sensors is, of course, in machine-readable code. However, instead of representing the angular shaft position in the standard set of sequential binary members, as given by the encoder disc in Figure 1, absolute encoders usually employ a special *grey code*, as shown in Figure 2.

In a grey code, the configuration of ones and zeros is chosen such that only one bit changes between any two consecutive numbers. Grey codes are used to help alleviate errors which inevitably occur when constantly changing numbers are being counted and stored. When a binary encoder is turning or a counter is counting binary numbers, any or all of the bits involved may change from one reading to the next. However, since these changes do not occur absolutely simultaneously in the real world, several transition states may occur between the true readings. In the worst cases, such as the transition from 7 (0111) to 8 (1000), for example, every bit changes. For a few nanoseconds the system is unstable. If by ill luck the computer reads the counter or the encoder during this moment of flux, any manner of garbage may be recorded.

Since the duration of the instability is quite short, the probability of a bad reading is quite small, and one erroneous reading out of every thousand does not matter for most applications in which numerous readings are averaged. A motor, for instance, is much slower in its response than an electronic controller, and it could not switch directions in response to one false signal. However, some optimal control applications may depend on near infallibility on the part of the computer (if not on the engineer), and in these applications erroneous readings are intolerable.

Of course, digital counting circuits may be designed to avoid this problem by synchronizing their operation with a clock and reading the count only during stable intervals, but the addition of such synchronization to an absolute binary-coded encoder represents an additional expense which may be unnecessary if a grey code is used.

Since the absolute encoder assigns to every location a unique coded number, it may be read directly by the computer, and much of the interfacing hardware which we describe here for an incremental encoder can be eliminated. With the grey code, when erroneous readings do occur, they are much less serious, since the error is at most one count.

On the other hand, an absolute encoder requires 12 or more separate sensors in order to attain good resolution, and is therefore rather expensive. An incremental shaft encoder which can identify locations within 0.04 degrees costs about $275. Others are available with much higher resolution, as well as less expensive ones. Incremental encoders require more interfacing hardware, but such designs are reasonably straightforward, as we shall explain.

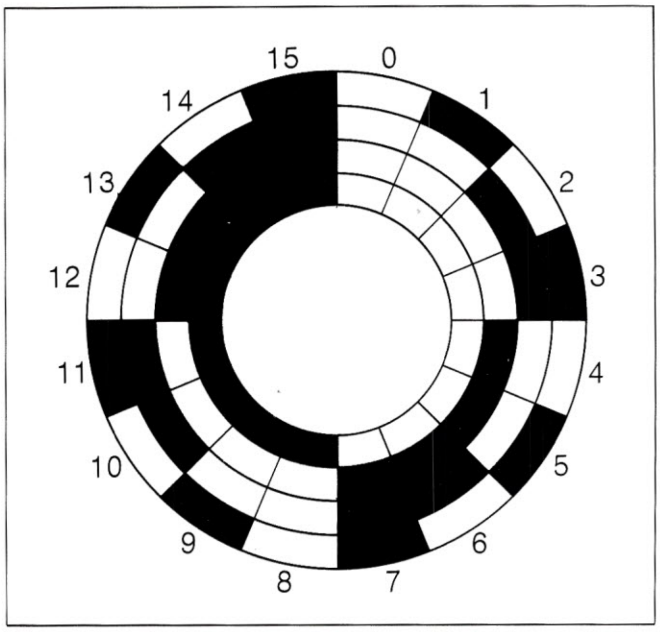


Figure 1. An absolute shaft encoder utilizing a binary code.

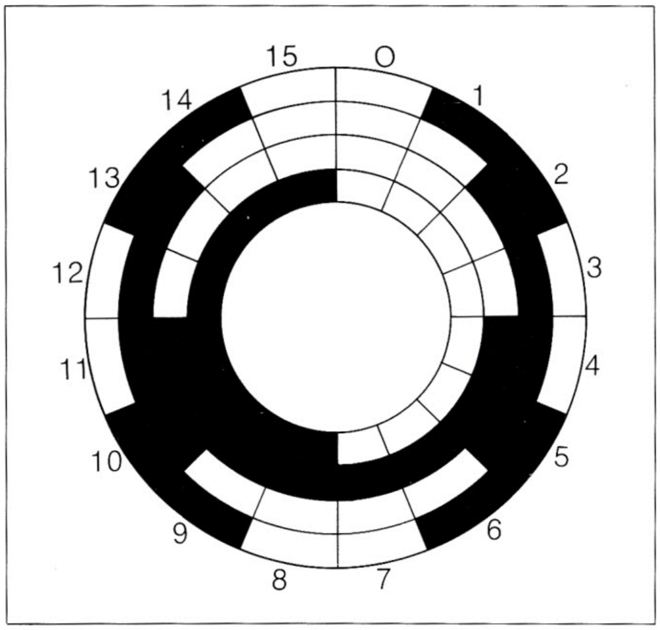


Figure 2. An absolute shaft encoder utilizing a grey code.

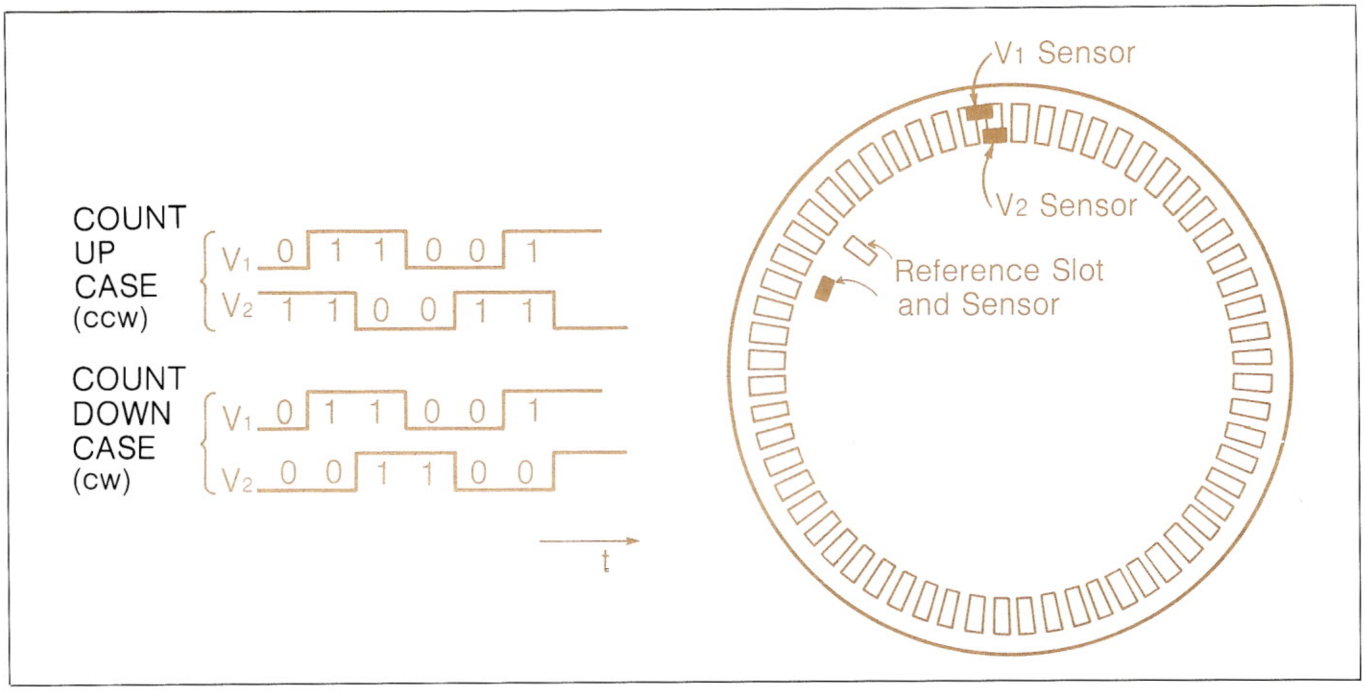


Figure 3. Output of incremental encoder.

Incremental Optical Shaft Encoders

Like the absolute encoder, the incremental encoder is a glass disc. However, it is imprinted with only one circular row of slots, all the same size and distance apart. One additional slot serves as a reference point.

Only three sensors are used with the incremental encoder, although the number of slots in the circular row increases depending on the resolution desired. Two of the sensors are focused on the row of slots. These are placed exactly one-half slot-width apart so that, as the disk rotates, a light shining through the slots produces detector signals that are 90° out of phase with each other. Figure 3 shows that if the disc is moving in a clockwise direction, one sensor (V_1) is always activated first; if the disc is moving counterclockwise, the other sensor (V_2) is always activated first. Thus, the pattern of the phase shift indicates direction.

The third sensor is focused on the reference point. Location can be determined by counting the number of pulses that occur from the time the reference point sensor is activated. The length of time required for a single pulse to be completed indicates velocity.

Position-Counting Hardware

While all necessary information about direction, velocity and position can be obtained directly from an incremental encoder, this information is imbedded in a continuous stream of pulses. It is too obscure for most simple counters, which are designed to rely on separate up or down counting signals to indicate direction. Therefore, we must provide special hardware to translate the pulses from the encoder into up and down count pulses.

It is possible to derive position simply by counting pulses directly from the encoder. One could count pulses from a single input, which, for the encoder used in our experiments, would allow us to attain an accuracy of 1/2500 of a revolution. Even so, it is necessary to consider both inputs, since phase information is needed to determine direction and hence to decide whether to count up or down.

Figure 3 shows the four unique states of the encoder, and the unique sequences of possible encoder outputs for continuous motion in each direction.

One could design a sequential machine to decode this complex of signals and output count up (CU) or count down (CD) pulses at appropriate changes of the encoder. Figure 4 shows such a design, where the state of the machine has been given the same designation as the "current" input. When the input changes, so that the input does not match the current state, the machine will change into a state which does match the input, and will output a CU or CD pulse as shown.

The design of a finite-state automaton to implement the state diagram of Figure 4 is reasonably straightforward. It requires two flip-flops and a few gates.

Alternatively, one could sacrifice resolution for simplicity and get a design which counts every cycle of the encoder rather than every state. Figure 5 shows one such design.

We have used a different design which utilizes the full resolution of the encoder but requires only one chip, a read-only memory (ROM), connected in a feedback structure.

The ROM used is a 32x8-bit programmable ROM, which

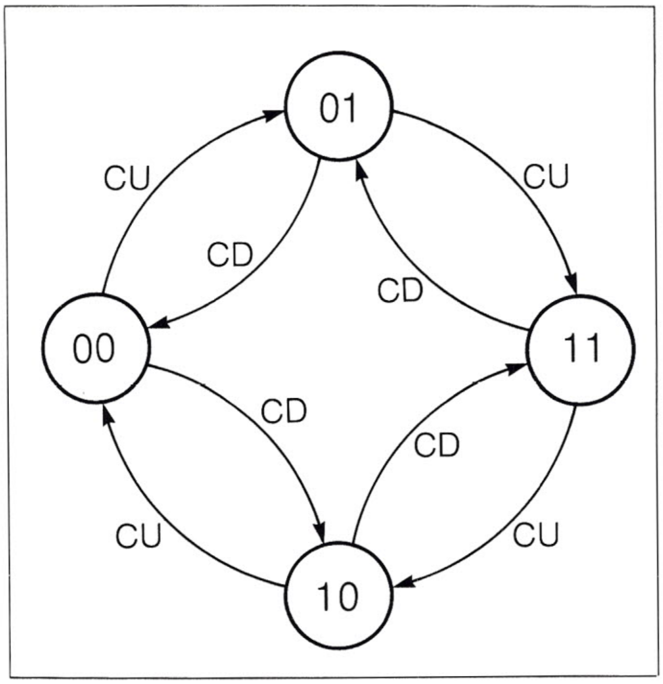


Figure 4. State diagram of a sequential machine to decode the state transistions of an incremental encoder.

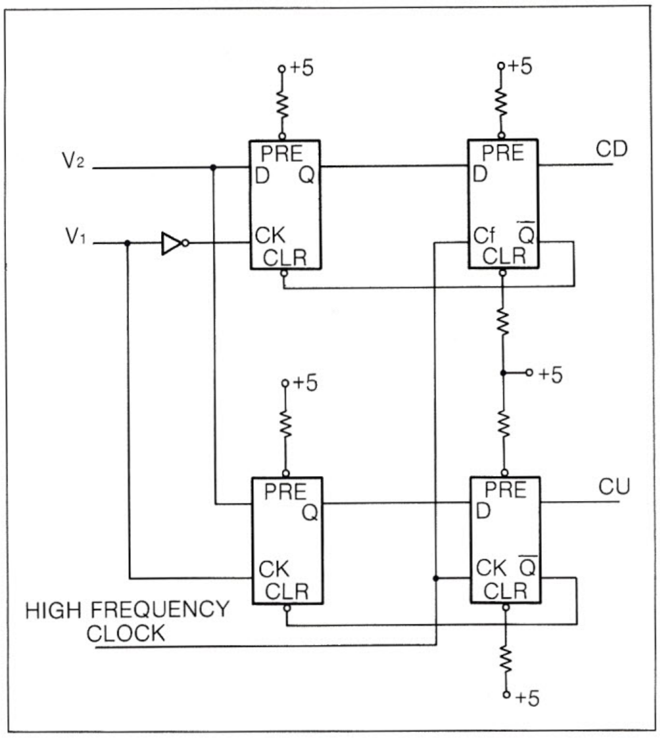


Figure 5. A low resolution position decoder (1 part in 2500 for a 2500 count encoder). This design is free of race conditions even for direction reversal. All flip flops are 7474s. The clock frequency must be much higher than the highest possible pulse rate on V_1. A rising edge indicates count up and a falling edge indicates count down.

has five address lines and eight data lines, connected as shown in Figure 6. Address lines A_1 and A_2 receive signals from the two encoder sensors. Data lines D_1 and D_2 output "up" or "down" signals to the counter. Address lines A_3 and A_4 are connected to data lines D_3 and D_4 so that they must contain identical information to be stable. The ROM is initially loaded with a stable configuration, that is, $A_3 = D_3$ and $A_4 = D_4$.

It is important to understand the internal operation of the ROM in this feedback structure. In this application, the ROM may be regarded as having 16 memory locations, each storing 4 bits. An example of how the data might be stored in the ROM is shown in Table 1 (page 8). Let us consider only one example.

Suppose the inputs V_1 and V_2 are in state $V_1 = 1$, $V_2 = 0$. Further suppose the output of the ROM is a 0010. (Don't be concerned at this point with *how* the output of the ROM came to be 0010, just assume that it is.) Then, since the lower two bits of the output are connected to the input, the address at the input to the ROM is 1010. Looking at address 1010 in Table 1, we see that the data stored there is 0010. The 10's in the lower two bits of input and output match, and, sure enough, the system is stable.

Now, suppose encoder line V_2 undergoes a transition from 0 to 1. We can see from Figure 3 that this change from 10 to 11 indicates clockwise motion and should result in a count down pulse. Consequently, the address inputs to the ROM change from 1010 to 1110. A few nanoseconds later, the ROM responds to this new input, by outputting the contents of location 1110, a 1011.

Since the low order two bits are different, address 1110 is not stable. As soon as the 1011 appears at the output, the address changes, since input *must* equal output on the bottom two bits, and the ROM sees an address of 1111. Again, a lookup is done, and a few nanoseconds later, the contents of location 1111 appear at the output, 0011. This time, the low order two bits of output equal input, and the state is stable. For as long as V_1 and V_2 both remain 1's, the output will remain 0011.

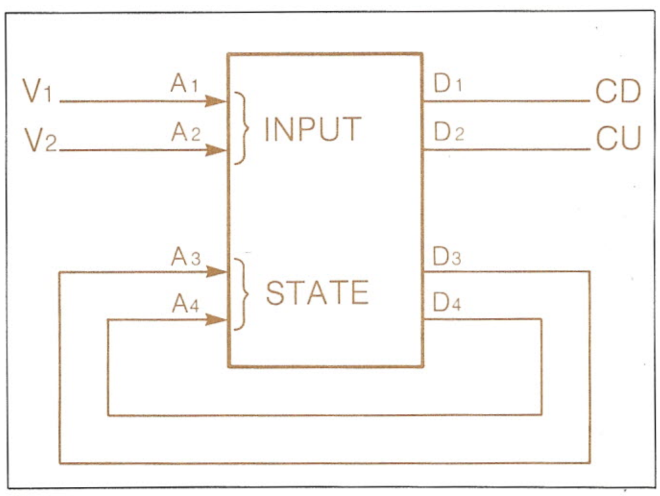


Figure 6. Organization of ROM.

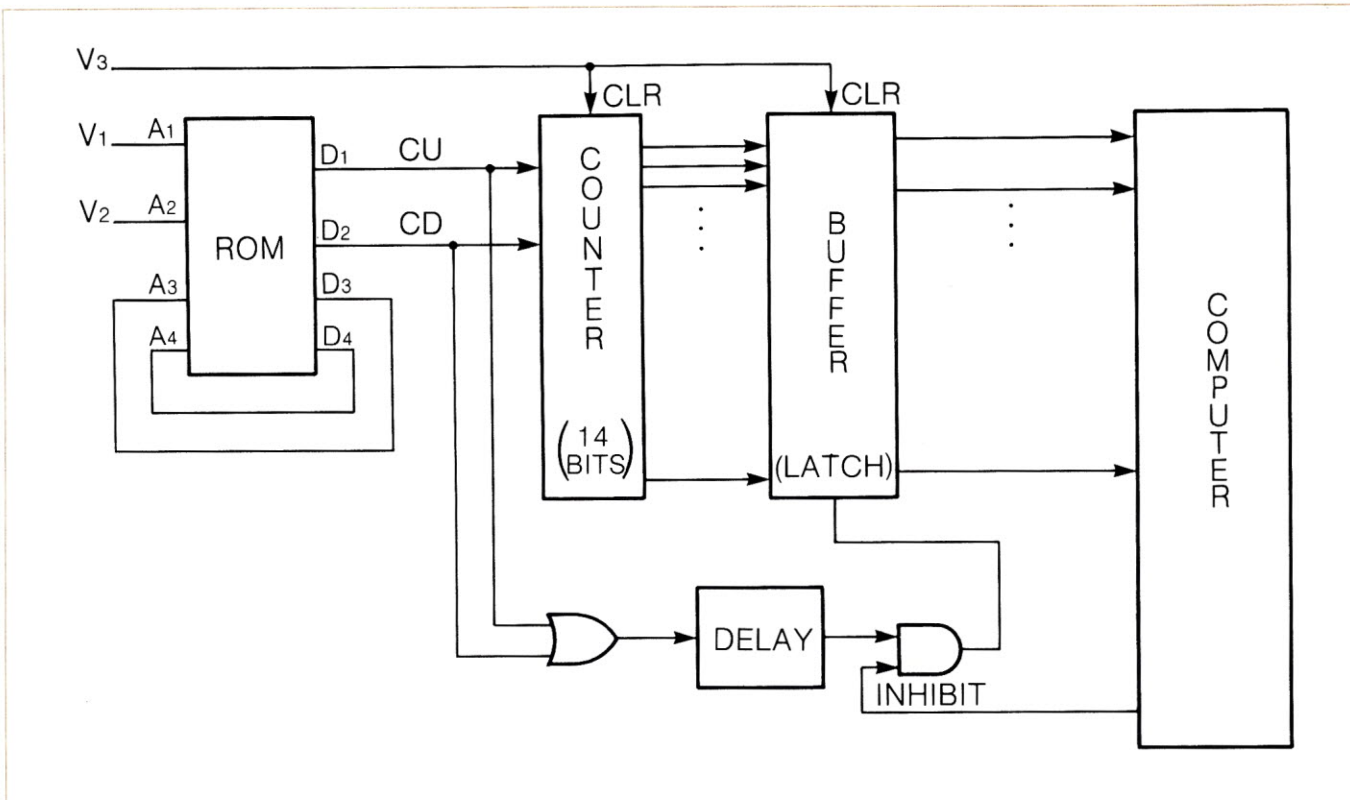


Figure 7. Block diagram of position hardware.

The important observation to be made now concerns the upper two output bits. Initially, the output was 0010, then it changed to 1011, then to 0011. In the process, the upper bit (the count down line) briefly pulsed to a 1 and then back to 0.

We have thus developed a system which decodes the direction and position information from an incremental shaft encoder and requires only one chip. Of course, making use of that data and remembering it requires more chips, a counter and a buffer memory, as shown in Figure 7.

As we mentioned in the introduction, there is a timing/synchronization problem resulting from the possibility that the computer may read the counter output while it is still changing. Users of the TMS 9900 are particularly prone to this problem, since the Communications Register (CRU) input reads bit-serial rather than latching all bits simultaneously. With a parallel input computer, a grey code could be used in the counter to resolve this problem. However, in this design we have used a commonly available binary counter and additional circuitry.

One way to eliminate this timing conflict is to provide an output from the computer which indicates "computer about to do a read," which will stop all counting activity. But then if a count pulse occurs during this time, it will be missed. To avoid this problem, an additional level of memory must be used which will read (in parallel) the contents of the counter each time it is updated, and hold that value for the computer. The "computer about to read" signal will then inhibit (we will call this signal the INHIBIT from now on) the loading of this memory. Figure 7 shows a block diagram of the complete position detecting system.

The count up and count down pulses operate as described on the counter, their logical OR is taken, delayed (to let the counters settle), and used to strobe the latch. When the computer is about to read, the inhibit signal (normally 1) will be set to 0, preventing the occurrence of the strobe to the memory. After reading, the computer sets INHIBIT back to 1, allowing the latch to be loaded once again.*

Circuit Description

Figure 8 is a circuit diagram of the position circuit as it is implemented. There are some slight differences from the block diagram, which was drawn for clarity, not accuracy. The actual up/down counters used, SN74193's, count on the rising edge of negative-true signals on their count lines; consequently, the CU and CD lines are actually 0 when

*One might also consider parallel peripheral circuits which are commonly used with 8-bit microprocessors and will be soon available in the 16-bit field. For example, the Intel 8255 can, in some designs, provide a similar latching function to that provided by the SN4374's in this design. (Latching only on request).

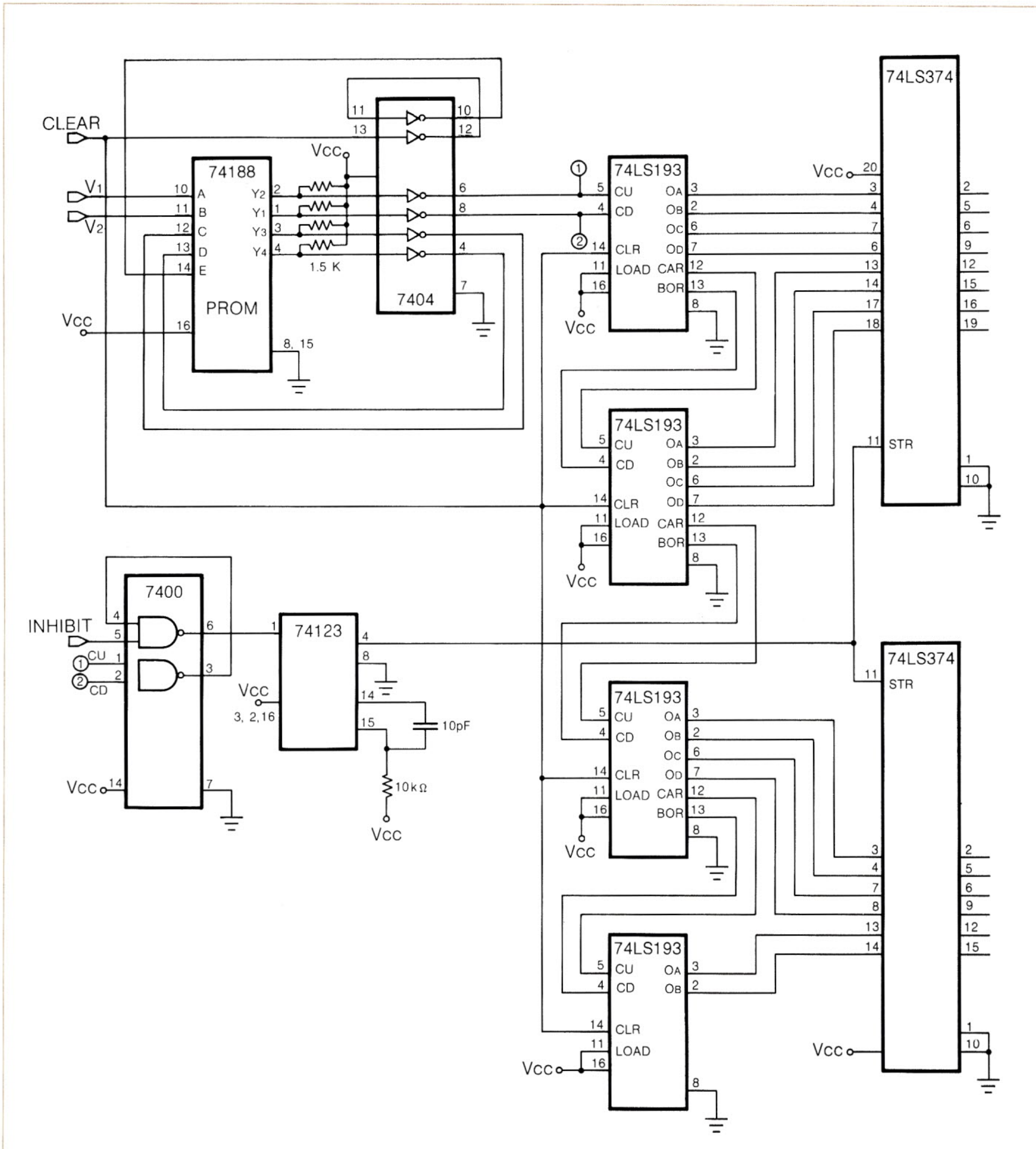


Figure 8. The position measurement circuit.

TABLE 1

	V_1	V_2	A′	B′	CD	CU	A′	B′
	0	0	0	0	0	0	0	0
	0	0	0	1	1	0	0	0
	0	0	1	0	0	1	0	0
Impossible	0	0	1	1	0	0	1	1
	0	1	0	0	0	1	0	1
	0	1	0	1	0	0	0	1
Impossible	0	1	1	0	0	0	1	0
	0	1	1	1	1	0	0	1
	1	0	0	0	1	0	1	0
Impossible	1	0	0	1	0	0	1	0
	1	0	1	0	0	0	1	0
Stable 10 state	1	0	1	1	0	1	1	0
Impossible	1	1	0	0	0	0	0	0
	1	1	0	1	0	1	1	1
Not stable	1	1	1	0	1	0	1	1
Stable 11 state	1	1	1	1	0	0	1	1

asserted. Since we are taking the OR of low-true signals, we can use an AND gate to trigger the strobe. Note that in Table 1, a 1 will cause a *low* output, and consequently the inverter chip is used, which also provides needed additional delay in the feedback loop. In implementation, to meet the low-true requirements of the 74193 one must also require the contents of the D and U columns of Table 1 to be inverted.

The reference pulse from the encoder, which occurs once per revolution, is used to reset the position counter to zero, and is indicated in the circuit by the signal CLEAR. This pulse is delayed as shown and used to address the second half of the ROM, which is filled ones so that the ROM feedback circuit is also reset to a stable starting state for the next counting cycle.

Design Considerations

A good engineer will usually consider making some sort of change to any design he sees. In anticipation of that, we provide a few pointers:

1) A *critical* point in dealing with encoders is that it is possible to receive arbitrarily short pulses from the encoder due to instantaneous direction reversals. This may be induced by mechanical jitter and/or motion around zero speed. Therefore it is essential that no pulses be permitted whose duration is less than the shortest allowable clock period in the electronic counting logic. This may be easily accomplished by using a low-pass filter followed by a Schmitt trigger on the encoder outputs.

2) The CU and CD pulses are very fast, being equal approximately to the propagation delay of the ROM. This pulse *must* be significantly longer than the pulse required for the counters, and don't forget that the counters are synchronous, but cascaded. The pulse length can be increased by adding delay in the feedback of the ROM.

3) The delay from the occurrence of the CU or CD pulse to the rising edge of the strobe must be greater than or equal to the settling time of the counters plus the setup time of the latch. In our case, this is 30 + 16 nanoseconds, and the delay shown is sufficient, but with other parts or logic families, the story may be different.

Hardware for Measuring Velocity

Since velocity is equal to distance divided by time, there are at least two ways to measure it. One could measure how many count pulses occur in a specific time interval, or one could measure the amount of time required by one encoder pulse. There are advantages and disadvantages to both approaches.

In the first case, one must choose a time interval sufficiently long to accumulate a number of pulses, in order to determine velocity accurately. For example, suppose the maximum velocity of the joint is one revolution per second. Then at this rate, our 10,000-count decoder yields one count pulse every 100 μs. For an 8-bit accuracy, we should allow time sufficient to accumulate 255 counts, or 25.5 ms. This gives us a new velocity measurement approximately 40 times a second, an update rate which is marginally fast enough for a small, fast robot, but quite sufficient for larger, more massive machines.

On the other hand, one could measure the length of a single encoder pulse. This yields an update rate which is quite high, but is at the same time rather noise sensitive. Despite this noise sensitivity, this is the approach we have used and will explain in this article. We will also explain methods for dealing with the noise.

The basic idea behind our velocity hardware is the measurement of the width of a single cycle from the encoder. This is accomplished by first dividing the frequency of V_1 by 2 using a simple flip flop,* producing the signal V'_1 then using a clock whose frequency is much higher than the maximum frequency of V'_1, and counting

*We time an entire cycle of V_1 rather than simply the time V_1 is high since the duration of a cycle is much more repeatable than the high or low period.

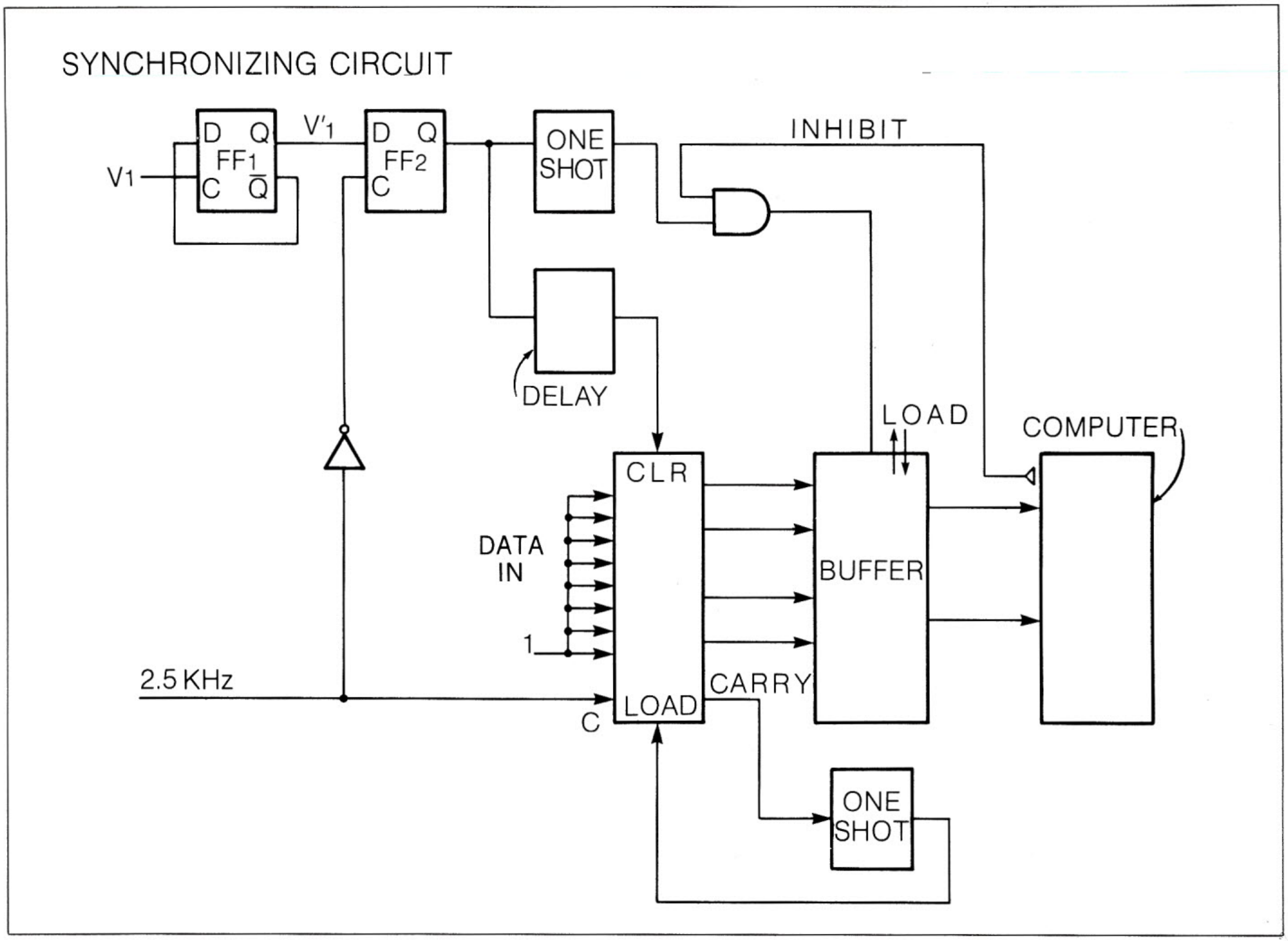


Figure 9. Block diagram of velocity hardware.

the number of clock pulses that occur while V'_1 is low. Again, assuming the same 2500 count/rev. encoder, with maximum velocity of 1 rps, we find the shortest period V'_1 can be low is 400 μs. A 2.5-kHz clock will give one count at this rate.

If we choose to use a 2.5-kHz clock, 255 counts will require 102 ms. Consequently, an 8 bit counter will overflow if it is clocked at 2.5-kHz and the V'_1 pulse is high for more that 102 ms. This corresponds to a velocity of one rotation every four minutes. Thus, with a 2.5-kHz clock and an 8-bit counter, we can measure any velocity from one revolution per second to one revolution every four minutes. We assume faster velocities are impossible, and slower velocities will be counted as stationary. With this system, the accuracy goes down at higher velocities, with a worst case error of $\pm 25\%$ at the maximum speed. While this is the worst case error on any individual sample, the 2.5-kHz is uncorrelated with the encoder, and measurement errors will tend to average out, even over a few measurements. Of course, at lower velocities, errors are much smaller.

Figure 9 shows a block diagram of a "quick and dirty" solution to the velocity measuring electronics. Counting occurs while V'_1 is low. That is, we time the "off" half of the V'_1 pulse.

As long as V'_1 is low, the counter is enabled for counting. Every 400 μs, the counter will be incremented by one. As soon as the rising edge occurs on V'_1 the memory will be strobed (a rising edge triggered latch is used), retaining the contents of the counter at that moment, and then, after the delay, the counter will be cleared. The clear to the counter is an overriding clear, and the counter will stay cleared, even though clock pulses occur, until V'_1 goes low again.

Note that, to avoid the possibility of a load signal to the latch occurring while the counter's outputs are changing, V'_1 must be synchronized with the clock. This is accomplished by the addition of a second flip-flop, whose synchronized output is used instead of the original V'_1. Also, as in the position circuit, the load pulse to the latch is gated by the computer INHIBIT signal.

The only remaining difficulty which we must handle is the possibility that, at low velocities, the V'_1 pulse is so long that the counter overflows. In this case, a carry output

from the counter occurs, triggering a one-shot*, which loads the counter with all 1's. At the next cycle of the clock, another carry will again trigger the one-shot and again load all 1's. Consequently the counter will always contain hex "FF" when the arm is stationary.

Determining Direction

The direction of motion needs to be considered at this time, i.e., the sign of the velocity. Our circuit up to this point has considered only the width of the encoder pulse, corresponding only to speed and not to direction. We have handled the question of direction by using one additional flip-flop, and using the CU or CD pulses from the direction determining hardware to set or clear (respectively) this bit. There is no race condition to be considered when interfacing this bit to the computer, since erroneous readings could only occur at zero (or very low) velocities, and in that case, it doesn't matter.

Determining Actual Velocity from the Measurements

In designing our velocity hardware, we made a tradeoff between the number of bits in our velocity counter, and the accuracy with which we could determine velocity. Also entering into the calculation were the maximum and minimum measurable velocities. Since we arbitrarily determined to use an 8-bit counter, we introduced significant errors at the high end of the velocity range. These errors could be reduced by using more bits and a higher clock rate, thus measuring the higher velocities more accurately, or by continuing to use eight bits, but with a faster clock, setting a higher minimum measurable velocity.

A third alternative is to anticipate these errors, and to allow them to average out. We have chosen this alternative by using in the computer program a simple low-pass filter. If V = determined velocity and V_M = measured velocity, we compute V by

$$V = 0.5V + 0.5V_M$$

Other choices of coefficients are possible, corresponding to more or less averaging, but we have found this simple filter to be quite satisfactory in our experiments.

The quantity measured by the hardware of Figure 9 is a measure of time, not velocity. To convert to velocity, one must divide a constant by the measured number. We considered at one time doing this division by a lookup table, utilizing another ROM. However, the $V = 1/T$ calculation has a hyperbolic graph, which at low velocities results in a large number of different times, all of which round off or truncate to the same values. Thus, by choosing to use an 8-bit lookup, we would have introduced errors at the low velocity end of the scale, due to round-off. We were already inaccurate at high velocities, and more inaccuracy was clearly undesirable. For this reason, we elected to do the division in the computer.

In fact, we have found it most effective to do the previously described averaging/filtering operation on the measured period data prior to performing the division using 16-bit arithmetic on the computer.

Conclusion

We have described special purpose hardware for determining position and velocity using data from an incremental shaft encoder and for presenting this information to a computer, taking into account the possibility of timing conflicts during reading.

We have included some concepts which are generalizable to a large class of digital hardware problems, including the rather standard but useful two flip-flop synchronizing circuit (Figure 5), and especially the use of a ROM and a delay as a one or two chip implementation of a synchronous machine.

Having provided this information, the best advice we can give is: don't take our advice blindly! That is, it is probably not necessary to use special hardware at all. We have often observed that, in a holdover from the time when computers were very expensive, engineers will sometimes interface to a microprocessor using hardware which is more expensive than the microprocessor itself.

The most effective, easiest to use, and most inexpensive hardware you can use is often the processor itself, or even a second processor. We developed this hardware for an optimal control application which required very tight constraints on software speed. Consequently, the addition of hardware was necessary. In applications with higher rotational speeds, or higher resolution encoders, it may also be impossible to use a microprocessor, due to its speed limitations.

However, many applications do not have such tight constraints, and the processor itself, possibly utilizing

*The authors normally advise against designing with one-shots, which are particularly sensitive to noise and prone to false triggering. The one-shot approach seemed to fit this application so well that it was used anyway, but readers are cautioned to follow layout rules carefully, and, in noisy environments, to use a sequential logic design approach to the same function.

interrupts, can be used to count the encoder pulses. If the processor includes a real-time clock, as many do, velocity determination can likewise be done in software. In an earlier report in *Robotics Age* (Vol. 2 No. 1, Spring 1980) we described a system which used a simple processor to implement path control for one joint. In that application, we used hardware similar to that described herein to decode velocity, but used interrupts to keep track of position in software.

In conclusion, one should carefully evaluate the cost-effectiveness of building special hardware versus using the computer itself. In applications which are not pressed for time, the latter is often the better choice.

Acknowledgements

The synchronizing circuit utilizing a single SN7474 which is described in Figure 9 has been around for quite a while and is extremely useful in a wide variety of applications. We suspect it has been re-invented many times.

The concept of using the state transition of the encoder (Figure 4) to provide an accuracy of 1/10,000 from a 2,500 count encoder was developed, as far as the authors know, originally by Clifford Geschke.

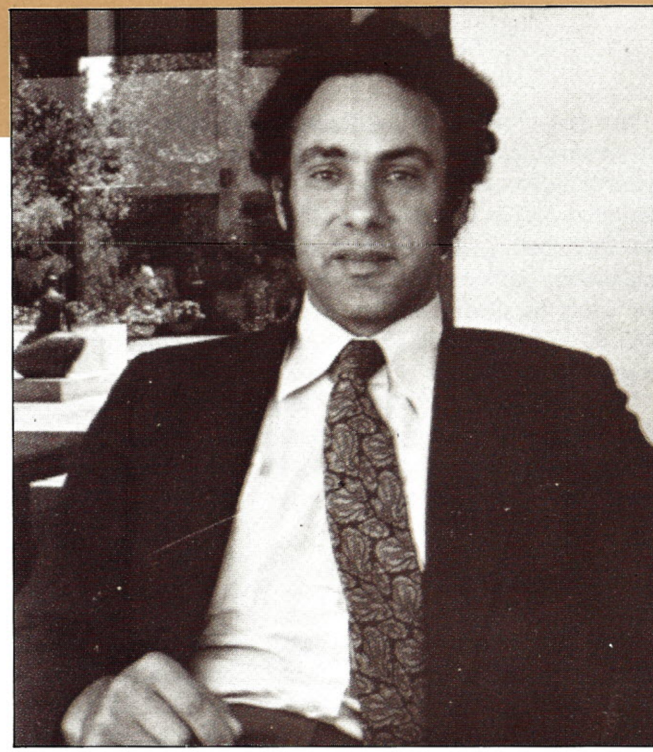
The use of the ROM to implement the state diagram of Figure 4 came out of a design projects class taught by one of the authors for seniors in electrical engineering at North Carolina State University. No single member of the group would ever accept credit for the idea.

About the Authors

Dr. Snyder is on the faculty of the Electrical Engineering Department at North Carolina State University, where he is also associate director of the Image Analysis Group. That group is deeply involved in research into computer analysis of images, with a current specialization in analysis of sequences of images as might come from a television camera. Dr. Snyder has just returned from a six month stay in Germany where he did research on computer tracking of objects moving in a television image.

Dipl.-Ing. Schött is an electrical engineer with the DFVLR, the West German Air and Space Agency. He has been involved in a number of projects relating to digital command and control systems, and is currently developing microcomputer-based control hardware and software.

ROBOTICS AGE INTERVIEW SERIES



By Jerry W. Saveriano

AN INTERVIEW WITH VICTOR SCHEINMAN

The inventor of the MIT and Stanford Research manipulators—and the driving force behind the PUMA industrial robot system—talks about the history and future of advanced robotics.

Robotics Age *is proud to introduce the first of a series of exclusive interviews with leaders in the rapidly evolving field of robotics.*

This series takes a look at the people behind the machines. A review of the past and a look into the future of robotics by the people who are making it happen. Internationally recognized scientists, researchers, industrialists and engineers share with us their knowledge of the field.

Our readers will get a deeper insight into roboticists and their robots—the innovators and machines that are creating a new technology.

The creator and interviewer for the Robotics Age Interview Series is Jerry W. Saveriano, Industrial Editor of **Robotics Age** *magazine.*

Victor Scheinman, at 37, is the inventor of Unimation's PUMA robot, derived from his earlier designs of advanced research robots for Stanford University and MIT. Credited by *Fortune* magazine as "the father of the 'new' robots," Scheinman, as a graduate student at Stanford, formed his own robot company, Vicarm, which was subsequently acquired by Unimation. More recently, he has helped form Automatix, one of the newest additions to the high-technology robot field, serving as its Vice President for

Advanced R&D.

In this interview, Scheinman discusses the development of his unique robot technology, how it led to the PUMA manipulator, and some of his latest concepts for advanced robot systems.

Vic, how did you get interested in robotics?

Well, in high school I participated in science projects, one of which was a word recognition system, with an electric typewriter printout. I built the solenoid actuators myself. Then, at 16, I graduated and went to MIT. There, in the early '60s, I worked an a control system using an ultrasonic transmitter and transducer, akin to the Polaroid ultrasonic range sensor available now, to measure wave heights and guide a hydrofoil over the water at a fixed height and at varying speeds. During the summers I worked for various aerospace corporations, including Sikorsky Aircraft and North American Aviation in Downey, CA. After graduating from MIT in '63 I worked for Boeing in Seattle, mostly in rocket propulsion. (My degree was in Aeronautics and Astronautics.) After 6 months there, I took a 9 month trip, starting and ending in New York, going westward all the time around the world. I visited friends, mostly in the far east, and looked at lots of little industrial operations in places like Thailand and Malaya. I got interested in Mechanical Engineering design.

A year later, in '64, I came to Stanford University, initially in the Aero/Astro department, but immediately switched into the design division of Mechanical Engineering. I got my master's after one academic year. It was a heavy year because I switched curricula in the middle of the year, and it's normally done in one full year. I continued on with the idea I might very well do a doctorate.

The Artificial Intelligence Lab was just getting going at Stanford under ARPA* funding, and I got a research assistantship to work on the design of a computer-controlled manipulator that was supposed to be very fast (that was the overall specification). The reason being that people at that time felt that no matter how fast the arm was the computer could always be faster and be able to control it, so why not build a very fast one. This arm design was started actually by Bob Piper, who was a year or two ahead of me. He had done some of the conceptual design; I continued with the execution of it, working 20 hours a week as a research assistant. The hydraulic arm at Stanford was a rotary actuator, servo-valve, 6-axis manipulator, somewhat like a small Cincinnatti Milacron T-3. About two years later we had a completely operational arm with a computer that was too slow to run the thing! We used a time-sharing system with a DEC PDP-6 computer, and the only time we could run the arm was at two in the morning when nobody else was using it, because it took the whole machine to control the servos.

Our goal was the complete control of the manipulator with the computer. The servo loops were closed within the computer which also, of course, performed the trajectory planning and motion control. Everything was done with the one computer, and this took a long time.

One thing we learned as a result of that project was that a hydraulic arm really isn't the ideal tool for the university environment, mainly because of some of the user hazard problems. Occasionally we'd break hydraulic lines, and you really couldn't get within the working range of the arm because if you did get hit it would be a problem. We made all our work tables and work environment out of styrofoam boards and blocks, so that if the arm really did do something wrong it merely crushed the styrofoam.

What about the so-called "Stanford Arm"?

That came later—I took a year off to go to Belgium where I studied fluid mechanics at a University near Brussels. I got a European Master's degree in fluid mechanics. Back at Stanford in 1967 I started doing work on the next generation robot for the AI Lab. We decided we wanted an electric manipulator, one that could be more easily programmed. For instance, we had learned some of the requirements for a good manipulator solution—having intersecting wrist axes, for example. We also had a better idea of the workspace and the performance accuracy we wanted. We were able to come up with better specifications than just, "make it fast."

In December of 1967 I was also fortunate in that George Devol of the Devol Research Co., original holder of many of the Unimation patents, gave a fellowship to Stanford, which I got, called the Devol Research Co. Fellowship. This enabled me to continue the new manipulator development full time. It was around that time that I met Joe Engelberger and part of the fellowship included a visit to Unimation in Danbury, CT, and a small tour of industry. That was my first contact with industrial applications of robots. I came back all charged up to really work on this new computer-controlled manipulator design. The design of the Stanford arm was the result of my work in 1967 and 1968. In spring of '68, I finished the design. It was an all

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**Advanced Research Projects Agency, a research arm of the Dept. of Defense—ed.*

electric manipulator that had four harmonic drives in it. It was all aluminum in construction, and had 6 axes driven by dc servo motors. Two of the axes used printed circuit type motors, and the other four used high-torque dc motors. I wrote my engineering degree thesis on the manipulator design, then decided I really wanted to work in industry. After I wrote the thesis Stanford asked me to build it. I spent a few months on it, but decided to start in industry.

I worked for a company in Menlo Park, designing advanced automation equipment. Up to that time, automation equipment was mostly relays and mechanical control systems, and I was very much committed to the idea that automation should be an electronically-controlled system. A year later, however, I returned to Stanford to finish the construction of the Stanford arm and get it to run.

The fact that the design came from Stanford got more people interested in building one. The first group outside of Stanford to build a "Stanford arm" was actually Boston University. Unfortunately, they only had a PDP-8 computer, (we were using a PDP-6 *and* a PDP-10!) and they had too many problems with it. In 1972, Marvin Minsky invited me to come to MIT to design a mini-robot under an ARPA grant. ARPA, by the way, was the prime funder of the artificial intelligence projects at MIT and at Stanford. I went to MIT in the summer of 1972 and designed the MIT manipulator, which is the model akin to the new Unimate 250. It was a six-axis jointed-elbow manipulator, electrically driven with six dc torque motors. I was very much committed to the concept that every component of the manipulator should be designed for the function it is intended to perform. Every gear was a custom gear; even the potentiometers were all custom made. The motors were all built out of component sets, so that all the shafts, all the housings, in fact, even the bearings were custom made. Another key feature of the MIT arm was its small size—it weighed a total of only 15 pounds.

Given that you already had some contact with industry, you knew what they wanted. It seems obvious that you designed this for light assembly work.

The MIT manipulator was originally designed to be an artificial intelligence laboratory tool—a desktop unit that a student could have on the corner of his workbench. The PUMA manipulator is built on exactly the same concept of functional, six-axis custom design, enlarged and given the features it needed to make it attractive for industry.

After completing the design, I returned to Stanford, where I built the arm for MIT. At Stanford I was working on a five-fingered hand which had 17 degrees of freedom. It turned out to be a very fancy piece of hardware—but not controllable, which was one of my big disappointments. Coming out with good algorithms to control multi-jointed fingers with that many degrees of freeedom was a difficult problem. In addition, I hadn't really worked out the tactile, or touch sense, which seems to be one of the keys to really good localized manipulation capabilities, such as manipulating an object in a single hand.

I also continued the development of a wrist-mounted six-axis force-torque sensor I had started at MIT. Another thing I was looking at was the use of optical encoders instead of pots for increased resolution and improving the linearity of the measurements of joint position.

During this period you provided manipulator designs, as well as functioning units, to a number of universities and research labs. Why didn't they design their own?

Partly because software was a bit of a black art then and was their primary concern. Also, the costs of custom design were high and this was a manipulator concept that seemed to work. The biggest problems were not in building the robot but in interfacing it with the computer—and then controlling the robot in an intelligent fashion which Stanford was the first to do, and then, of course, other people followed.

After having delivered the first arm to MIT they ordered a couple more, and other people started getting interested in the robots. I really couldn't handle the requests on an individual basis, so I started Vicarm in May of 1973 for the purpose of manufacturing and selling robots. About a month later we had our first facility. We bought a small machine shop in Mountain View, CA, where we had two lathes, a milling machine, and all the proper equipment.

You were still working at Stanford?

I was still on the staff at Stanford, designing new advanced manipulators and components that fit them. By that time I had designed computer-controlled turntables and I had built computer-driven laser scanning equipment for 3-D imaging. I also had computer-controlled vises, computer-controlled screwdrivers, and other automated tools.

After founding Vicarm I resigned from Stanford because of the potential conflict of interest. Since I liked the connection with Stanford and liked to do development, I went back to student status to continue work toward my doctorate at Stanford.

How did you price the arms Vicarm was selling?

Well, the cheapest I ever sold was the MIT arm (the forerunner of the Unimate 250) at $4,000, for the manipulator and simple controls. Three years later, when I had learned the ropes and realized what it was really costing me to develop new systems and invest so much money into new developments, that price had risen to approximately $35,000 for a complete system. But of course, from $4,000 for a bare manipulator to a $35,000 system represented a siginificant increase in the versatility and usability of the robot. I had added computer control, software, and a user interface for a complete stand-alone system, the Vicarm system. Basically, Vicarm was originally founded to supply the needs of research groups for computer-controlled manipulators to do artificial intelligence-type robotics research. After MIT, my first real customer was Texas Instruments Corp., followed by General Motors, Western Electric, The National Bureau of Standards, the Navy, and several universities.

Was this the first computer-controlled robotic arm?

I wouldn't say it was the first computer-controlled robotic arm because what robotic arm means I'm not sure. But it was the first really usable computer-controlled manipulator which had more than just simple point-to-point capabilities. That was the siginificant feature of the Vicarm system. It was designed to be controllable and programmable at a high level. The control systems were "multimode servos" with the ability for force control, position control or even velocity control. Software wasn't worked out for all of those levels of control but the provisions were there. The manipulator eventually had an arm solution as far as the manipulator was concerned—you could position the manipulator in Cartesian space even though it didn't have a rectilinear-type configuration.

So Vicarm was really leading the field of robotics at this time?

It certainly did in the area of practical robotics and what I call true robotics, giving the robot, this manipulator, the semblance of some intelligence in the sense that it was programmable to an extent greater than the ability to move from one precision point to the next precision point. We were able to create straight line motions, move it smoothly between points—put in higher level functions such as the approach and depart function, integrating lots of features which were not possible without a computer.

It seems to me that, at some point, whether anyone realized it or not, that true robots "happened." Did anyone know or say at the time, "Hey, this is the first real robot!"?

No, I don't think we were really aware of it ourselves because, although the hardware, true, was the physical realization of the robot, in reality the robot was more than just a piece of hardware. It was the electronics, the controllers; in fact, it was a room full of computers in the early days. It was literally a room full.

The feature of the Vicarm system was that it was a low cost tabletop system. Because I had familiarity with the DEC computers, we decided to continue along that line, and I knew that the DEC LSI-11 was on the drawing board, and rumor had it that it was going to be really nifty. So I planned for that computer and, interestingly enough, that was probably the smartest move I made. One of the key requirements was the fact that we had to do a lot of computation in real time. The LSI-11 was the first computer that could do the required computations on a low cost compact system, albeit with very good software. We had excellent programming, primarily by Bruce Schimano, who developed VAL, the *V*ic*A*rm *L*anguage (which later became Unimation's *V*ersatile *A*ssembly *L*anguage).

There were many tasks that we were able do because, of course, we had the computer control, but also because we had a very intimate interface between the manipulator servo system and the computer. We were able to monitor motor drive currents; we were able to monitor servo errors—all sorts of things like that which enabled us to enhance the capabilities of the manipulator just through the servo systems. We were able to do tasks like block-stacking or block-sorting without the use of vision, or other types of sensors—provided, of course, the robot was able to grip the block. Vicarm also produced some of the force-torque sensors that I had developed, among other things.

Let's talk about the transition from Vicarm to Unimation.

In 1976, I decided Vicarm couldn't really continue in the same way we had been. I was dealing on a personal basis with all our customers; we had rather high development costs, and I was very eager to continue the development of the robots. We also felt that the customers really wanted a manipulator which would be standardized in such a way that if they bought one, they could say, "Well, if this is good, maybe we could get manufacturing to buy it and we'll take a hundred of them." So I started looking around for some organization which could either help me grow or

with whom to share my technology. I talked to a number of companies here and there, in the States and even overseas. We were profitable at the time, believe it or not. Of course, that was because we were very careful to get orders before we built them. Our deliveries always ran six months or longer, and we were very lucky that we had only very large, understanding, patient customers. I also knew General Motors, having had some experience with the original Stanford arm and aware of the MIT arm (small Vicarm), was starting to think of the PUMA manipulator. I knew that GM was interested in dealing only with manufacturers who had had the ability to deliver in the volume and support the product in the volumes they wanted. In a sense I really was out of the picture in the form that I was. We were just too small to do anything significant.

As a result of my looking around, in January of 1977 Vicarm became the West Coast Division of Unimation. Our first specific mission was to write Unimation's proposal to General Motors for developing the PUMA manipulator. A few months later we were happy to be awarded the contract to develop the manipulator for General Motors.

Was the award a foregone conclusion? Did GM influence Unimation to acquire Vicarm?

No, the PUMA contract was won on a competitive bid basis—to my knowledge there were several other bids. We knew that GM was coming out with a request for proposals, and GM knew that the team of Unimation and Vicarm would be a formidable team in making a proposal. Also, it was generally agreed that a small electric manipulator would be a nice addition to the Unimate line and, for that matter, an addition to the world community of robotics. I saw it as a very good opportunity to apply Vicarm technology and, through Unimation's ability, to really implement it on a larger scale.

Wasn't it intimidating? Here was a group of college students and part-time entrepeneurs suddenly jumping into big business with Unimation and GM, each the largest corporation in its field.

I had a lot of concern. For Vicarm's technology to gain the respect that we thought it deserved we had to market it to more than just the research community. We were a small organization—remember the Vicarm system was evolved by, at the maximum, five people, nobody really working full time, over a period of years—but to successfuly apply this technology would take a large organization which could have the service, maintenance, and which could have somebody to answer the phone almost 24 hrs. a day.

Did you have any problem gaining credibility, with being taken seriously by the industry?

Well, ultimately the Vicarm technology sold itself, but you've probably heard some of the stories of the first shows I went to. The first SME robot show was in Chicago in about 1975 or 76, and I remember flying there with a robot under my arm, the little MIT arm, and not having a booth at the show, not knowing the procedure for getting a booth for the show, trying to rent a booth for the show and being told there weren't any available, and so I set up my robot in the hall. It lasted in the front hall of the exhibition for about an hour before I was asked to leave, at which point I proceeded to demonstrate it on the front steps.

Of course, many of the people at General Motors and other companies remembered that. A year later, the SME was much more receptive to the Vicarm system than it had been and did agree to give me a booth. I remember that my advertising, or my spiel, at the next show was "the smallest robot is the smartest robot!" Indeed, The Vicarm system did consist of probably the most powerful computer in any of the robots at the show at the time, and of course, the most sophisticated robot control and programming language, the VAL language.

Given the small size of your company, though, wasn't it difficult dealing with industrial firms?

There was tremendous difficulty in dealing with anything but a research group in any of the companies. There was no way I could really even consider supporting any robot in any factory environment. After we became part of Unimation, though, we had the PUMA project, and grew from the initial two of us, Brian Carlisle and myself, to about eight full-time employees.

In about a year we had designed and built the first prototype manipulator system. Some of the key improvements were that we had gone to optical position encoders on all the joints of the manipulator, we had a dedicated microprocessor in control of each joint so we had much more sophisticated servo systems. We still used the LSI-11, and we had made some additions and enhancements to VAL. The first prototype of the PUMA was delivered to General Motors about May of 1978, and GM started the first tests. In the meantime, we developed the industrialized version of the Vicarm MIT manipulator, which became the Unimate 250.

Photo by Mark Montano

"Manipulators have been getting more and more precise in the past decade. In the next decade I think we're going to see a trend toward less and less precise manipulators...but when put into the total system the end result will be greater accuracy."

How were your relations with Unimation? On opposite sides of the country, there must have been difficulties, especially given the differences between the former Vicarm's operations and Unimation's.

We did all the prototype development of the PUMA on the west coast, the electronics, the software, and the mechanical design. The interface to the East Coast was sometimes strained because of the separation, which meant that when it came down to production of the PUMA we did have some difficulties.

I think there was an education process involved. It was bidirectional. We in the West Coast Division learned a lot about industrial applications of robots, the industrial requirements of robots, and also about manufacturing them. The people in Danbury, Connecticut learned a lot about computer-controlled robots, the need for software development facilities, the need for a good understanding of the new electronics—microprocessors, and even the special requirements of small electric manipulators. They also learned they don't necessarily use the same tools to make a PUMA which is alot more delicate machine than a big Unimate.

After about two and a half years as general manager of the West Coast Division of Unimation I again found that I was spending more and more time worrying about manufacturing problems, administrative problems, and engineering changes—really supporting the manufacturing operation from the west coast I also realized that if I did not return to Stanford to complete my dissertation I would probably never be able to do that. Finally, in June of 1979 I left to Unimation to return to Stanford University. I should add that about a year earlier I had gotten married and we wanted a family. I saw this as a good opportunity to change from the hectic 50-70 hr., 6 to 7 day a week pace that we were running at to something where it might be possible to raise a family.

But then less than a year later you joined Automatix. Does this mean you've changed your plans?

Well, as has been my fate in the past (or at least my experience) I can't resist exciting new opportunities, and early this year I became one of the founders of the new company called Automatix, which is located in Massachusetts, whose objective is the development of robot automation systems. As vice president of advanced systems, initially on a part-time basis, I have been working on some advanced development projects which have potential futures in the field of robot automation. I'm also still working on my doctorate at Stanford.

With all the high-power talent that Automatix has attracted, can we expect to see new exotic robots being developed?

Our intent is to build complete systems. If the systems require hardware that cannot be obtained on the current world market then we will build the system. We will be building specific components for systems.

I might say that one thing that people underestimate is the time needed to develop a manipulator system. It's one step to go from a concept to a prototype to real production and deliver reliable equipment. It's not practical for Automatix or anyone else to consider trying to develop a new machine and market it in a short period of time.

But you yourself got into the business on a low-key, entrepreneural basis. What about others trying to do the same? Are you saying that that can't happen today?

No, I think it can happen today. I think it is a bit more difficult to get into the industrial environment today as a robot manufacturer on a one-person entrepreneural basis

because at the present time there is so much venture capital and the industrial interest in robotics by large corporations. But it's certainly possible. Two of the things that have enable people to get into robotics on a small scale basis and have chances of success are the ready availability of some relatively low cost computer systems, the Apple computer, TRS-80, the TI systems, etc.—ones I could very well have used several years ago. And also a better understanding of the software requirements for good manipulator control—that's also much more available now. Now its possible to go out and find some papers on solution programs for manipulators, and write manipulator solutions that can be executed on a TRS-80, in a reasonable period of time, whereas several years ago it was difficult for the hobbyist to develop those solutions at home. Also, as an outgrowth of, for instance, floppy disc technology, even low-cost mechanical drives are available, which means low-cost manipulators can be developed which potentially have a niche in the industrial manufacturing world, such as the Microbot, whose drive systems are floppy disc stepper motors. One of the things I want to caution hobbyists on is that I'm still absolutely convinced deterministic computation is a necessity for good robot control, even with sensors. Sensors provide the ability to do a lot of adaptive type of control but the algorithms and computations are all very deterministically based. That means that the hobbyists have to have at least a reasonable understanding of mathematics, of coordinate transformation and the mathematics of manipulator solutions and trajectory planning to really make a contribution to the field of robotics.

An interesting thing about robotics has been that if you look at even all the effort that has gone into robotics today, the actual amount of everyday use of this robot technology is still very, very limited. Until we get sensors, until we have complete systems running and a larger resource base of more versatile software, every application will require lots of special engineering, even the simple ones. This has limited the versatility and the applicability of even the smartest robots today, even the PUMA type of robots. From the hobbyist standpoint, I think we are not yet at the point the true household robot can be built. In fact, I think that that's something that's still a little bit out of reach—at least for the next few years.

I'm interested in the development of robotics and artificial intelligence as a science. Most people, including me, think of MIT and Stanford as the center of this effort.

Of course, they have been. The MIT and Stanford artificial intelligence labs were the original ones, founded by Marvin Minsky at MIT and John McCarthy at Stanford University. There are other universities, more recently, who have started doing robotics research, but back in the '60s the two centers were MIT and Stanford.

At that time, it was expensive to buy lots of computer power, and, in fact, it was ARPA who was able to make these AI centers come into being. ARPA was one of the few organizations who, as part of DoD, had the money to do it. They saw a need for work in the field of artificial intelligence. Back in those days people talked about the "automated battlefield," but I personally never saw any directives from ARPA saying "Thou shall work on the automated battlefield." In reality, we had free rein, but it was ARPA who had the funds and foresight to develop these centers. Of course, now that computation capability has come down significantly in cost and is much more widespread, we have new centers developing.

It's interesting, to the general public work in robotics is very glamorous, and of course, the true embodiment of the popularized notion of a robot, the walking talking human emulator, is indeed very glamorous. But to those working in the field, progress has been very slow and evolutionary—a natural outcome of lots of very hard work and very logical development.

It took from 1972, from the start of the Vicarm project to around 1980 before the designs became industrially viable (in the PUMA and the Series 250). That was eight years of work. It also took another five years before that of work purely in the universities developing the basis for the control computations of the manipulator.

I'll give you another example—the original goal of the Artificial Intelligence Lab robotics effort at Stanford University, as set by John McCarthy around about 1964, was that we would try and design a manipulator and robot system with the vision, the language understanding capabilities, the planning and control software—everything that would be required to assemble a Heathkit color television set. In 1965 we bought the Heathkit television set. In 1966 the Heathkit color television set got assembled by a few students. About 1975 the Heathkit color television finally gave up the ghost, having operated satisfactorily for 10 years, and now sits in a dark closet.

That project was a bit ambitious. Professor McCarthy was one of the founders of the word artificial intelligence. He seriously believed, as a lot of us believed 15 years ago, that within five years or so we would be able to do something like that. I personally believe that there will come a day when we will be able to assemble the Heathkit television set, but by the time we do Heathkit will have come out with a model that all you have to do is figure out how to get it out of the cardboard box and plug in a single

chip. Accomplishing some of the tasks that people do, as everyday ordinary tasks—washing dishes, taking garbage out, washing the dog—is not something you can do overnight.

So far we've covered about the last 20 years of robotics, and it does seem, from my perspective, to have been a series of fairly small, logical steps, although the end results are already pretty impressive. The question is, will it continue in this evolutionary way, or are there some revolutionary breakthroughs that might happen?

As an engineer I feel that progress in the field of robotics is generally going to be of an evolutionary nature, not a revolutionary nature, in the sense that the steps and the progress will be generally ordered and keyed to the amount of effort that goes into robotics development rather than significant radical breakthroughs. There are potential areas for these breakthroughs, that's true, but I think in the next few years it's going to be mostly evolutionary.

The potential for revolutionary breakthroughs may occur in the possible applications in the field of microelectronics and integrated circuit technology. One of the areas I've been looking at is the possibility of taking integrated circuit technology's ability to photographically generate patterns on silicon wafers or other materials and etch those patterns into layered circuitry and applying it to the development of mechanical systems. Imagine that you're able to photochemically generate mechanical circuits rather than electronic circuits. We could even see the ability to generate little micromanipulators the size of a mosquito. By using some of the potential micromechanic technology and having the ability to replicate these mosquitos (or whatever you may want to call them), we may very well be able to build up fantastic capabilities from an opposite direction—even an entire manufacturing plant on a tabletop.

That's certainly revolutionary, and it could effect the way things go. One of the potentials is that the marriage of micromechanics and microelectronics would of course give the micromanipulator computational capabilities and intelligence—in the sense that the computer and electronic circuits would be etched into the micromechanical arm just as we create a microelectronic circuit today. I haven't thought that out very thoroughly yet, but that is an area that I've been considering.

So the robot world may one day be a microworld. That's certainly a radical departure from our present notions of the manufacturing environment.

Yes, but that's an example of what could be a potentially revolutionary development. What's more predictable are the kinds of changes I've been exploring in my recent research on the next generation of robots.

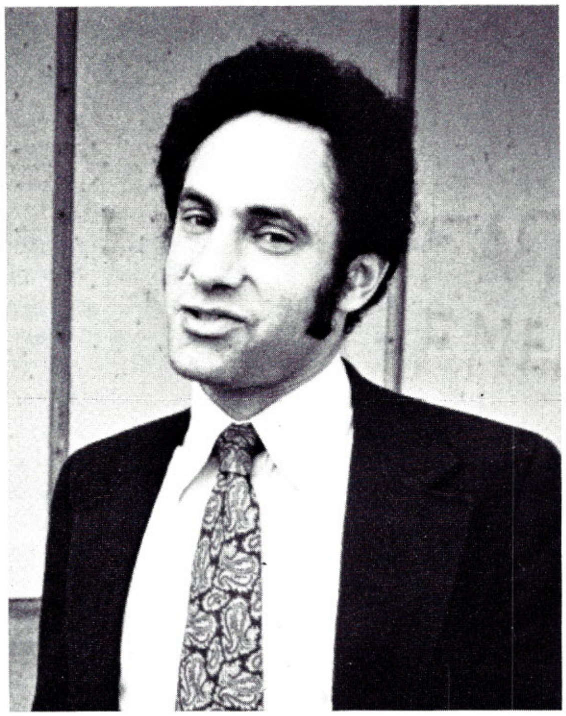
We talk of robots as being machines which perform human functions, and generally expected to be working in a human environment (or environments fit for humans). My feelings is, in the years to come, as robotics become more and more an accepted technology and robots are applied to all aspects of production (that includes machining, assembly, packaging—whatever), new products will be designed for production by robots rather than designed for manufacturing by people.

Rather than think about robots working in the people world, there is no reason to discard the notion of robots working in a robot world or robot environment. We build factories today for people to work in and work with machines in. There is no reason why we can't also design factories for robots. In reality they may be designed so that a person would never come into the factory. If the person were to communicate with the robot, the robot would come out of the factory.

Traditionally robots have worked in positions that a person might work in—on the floor in front of a machine, alongside conveyors, or something like that. In a robot environment there is no reason why they can't hang from the ceiling or stick out from the walls, they can throw parts from one robot to another because, of course, the environment can be very carefully controlled. The robot can work within the workspace of other robots. There is a big difficulty in industry right now of putting a person within the workspace of the robot. In a robot environment there is no reason why a robot can't work within the workspace of other robots.

We can afford to use new types of sensors and other technology which would be very risky within an environment where there are people. For instance, possibly using high powered lasers to do welding or heating operations in assembly, whereas if a person were in that environment it would be very dangerous. There is no reason to keep a plant at 65-75 degrees fahrenheit. You could keep it at 0 degrees if that helps, or elevate temperatures if that helps. There are all sorts of things that can be done in the robot world because all robots could be controlled by some sort of supervisory control computer. It can be very well-defined if necessary, which could reduce the need for sensors, or even reduce the complexity of some of the mainpulator elements.

Some of the other things I'm looking at are reconfigurable robots, actively reconfigurable robots that can change their configuration to suit tasks. They would be able to



"...in the years to come, as robotics becomes more and more an accepted technology and robots are applied to all aspects of production (that includes machining, assembly, packaging—whatever), new products will be designed for production by robots rather than designed for manufacturing be people."

change their own configuration themselves—add an extra joint, add an extra link, make themselves longer if they have to reach further, or make themselves stronger if they have to lift a heavy weight for a particular task. In other words they have a supply of parts. You can imagine the concept of a robot part stockroom. Rather than going out to get a special tool you get a special link or a special joint.

These are all things that you can do in a robot environment. Instead of having, for instance, an employee pool, where people are assigned tasks for each day of operations, there is a robot pool. The robot bin contains lots of robots which are used as needed. These are certainly some way out concepts, but they're basically some of my early thoughts on a practical realization of an environment for robots and a robot world. In fact, I'm just starting to work on the first realization of these concepts at Stanford University as part of my research in the field of automation.

It seems to me that the mechanical side of robotics has reached a high degree of development in the physical implementation of manipulators and is really reaching an area of fundamental physical limitations. However, developments in the software and in artificial intelligence have really only just begun, and, the potentials seem relatively unlimited. Is this really the case?

Yes, I think it certainly is. In fact, I think if you look at the level of robot development at the present time, the body in the PUMA manipulator and some of the other recently announced manipulators are probably going to be about the highest level of precision that we are going to see in manipulators. Manipulators have been getting more and more precise in the past decade. In the next decade I think we are going to see a trend toward less and less precise manipulators. As we develop improved sensors and higher and higher level control systems and software for the manipulators, the inherent precision of the manipulators will decrease. But when put into the total system the end result will be greater accuracy.

The level of precision built into the mechanics is at or near its peak at the present time. Of course, by reducing the mechanical precision requirements, systems cost can be reduced somewhat. The manipulator complexity can be reduced. There is no reason why suitable external sensors can't take all the positional encoder data for the manipulator. As I've mentioned we have lots of precision gearing in the PUMA manipulator, there is no reason why that has to remain, although it has its advantages.

So there's got to be less emphasis on mechanical devices and greater dependency on the software. I see it as a coming "era of intelligence," in which increasingly more is done in software, while less and less is done in the

mechanical world.

Yes, well as you know, the objective of the new ICAM (*integrated, computer-aided manufacturing*) efforts is to have the total manufacturing process controlled from the CAD (*computer-aided design*) data base. There's no reason that can't be be extended right down to the product assembly and packaging.

There's been great concern recently with the productivity of American industry. What impact do you think that this new technology will have in the near future?

American industry has traditionally been rather conservative about implementing new automation technology—especially compared with Japanese industry. I think there's a certain resistance in putting down the large capital outlay. The risk of new technology is very high because of the cost if it does in fact fail. The attitude has been, "if it works, don't touch it!" I have hopes because I think many of the large US corporations are now realizing that major decisions are necessary in respect to increasing their own individual productivity. They're not competing against other American companies any more as much as they are foreign corporations. They are going to have to take some of the measures that these foreign companies are taking. They are going to have to make the necessary investment, probably in robot automation. I think in the next 5 to 10 years we're going to see investment in robotics by American industry on the same scale (or maybe an even greater scale) than by foreign corporations.

It seems that this inertia regarding innovation and change is very fundamental. You've pointed out that even within the field of robotics, the "first generation" roboticists, who are coming from a machine tool and hard automation background, have had trouble dealing with the technology behind the "new robots" that you have developed. Do you envision new kids coming out, full of ideas, that you have trouble talking with?

Oh, I have trouble today! I definitely think that the forefront of robotics has now been transferred from the traditional manufacturing engineers, who are essentially trying to design some fancier automated manufacturing equipment, to—call it—the new breed of artificial intelligence, computer science, mechanical engineer designer types. I think that in the next couple of years it's going to be transferred to maybe even a newer breed who has even more emphasis and more involvement in microprocessors and software and programming capabilities. There has definitely been this sort of transfer. We haven't talked much about sensors, but in reality I think the keys to the future of robotics are in the sensors, and that's what I call the "system," or total feedback loop.

What would you recommend to the neophyte roboticist as to education and how to proceed?

I strongly encourage a person to get as much an education as he can. A good academic background with strong emphasis on microprocessors and some mechanical engineering to really understand the mechanics of the manipulator and the design concepts involved. A strong software background is essential, including assembly language as well as high-level language programming. I also recommend digital electronics design. As I mentioned earlier, I believe very strongly in good deterministic software and programming, and this requires a thorough math background. One of the things that I lack and I see would help me alot more would have been a little more industrial experience, that is, experience working as a manufacturing engineer for a while could help a lot in getting a feel for the requirements of real world manufacturing and real world industry.

Vic, Fortune *magazine called you "the father of the new robots." Do you feel comfortable with that mantle?*

Well, I'm honored to have been so designated, but I would like to give credit to the other people who have helped it all come about. I see my function, certainly, as having the vision to put the time, effort, and some of the financial resources into developing the modern robot system, but I didn't do it entirely alone. I sought help and got it as I needed it. Without that help I couldn't have done it.

Although it may appear from the outside to be a radical innovation, the funny thing is that to us working on it, it was all a logical progression, a slower progression than I think we envisioned when we first set out sixteen years ago. But as to where it all ends, there's no real answer.

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ROBOT VISION FOR INDUSTRY:

The Autovision™ System

by
Arnold G. Reinhold
and
Gordon Vanderbrug

Automatix Incorporated
Burlington, Massachusetts

Advanced robot technology such as computer vision is rapidly moving out of the laboratory and into practical applications in the demanding (both physically and economically) factory environment. With the introduction of the Autovision system, Automatix joins the growing number of high-technology firms engaged in the marketing and application of these developments.

A Brief Review of Machine Vision

Computer processing of visual images has been the subject of an enormous amount of research in the past 25 years. Almost since the invention of the computer, people have tried to couple computers with television cameras to develop a machine that could see. This technology has had some limited success in applications such as interpreting aerial photographs, guiding "smart" bombs, and counting red blood cells and chromosomes, not to mention broadening our understanding of the perceptual process.

In light of the hopes and effort invested in it, however, the spread of this technology must be considered disappointingly slow. There are two main factors holding back machine vision: First is the enormous amount of data represented by a TV image. A typical black-and-white home television picture requires about 8 million bits of information for faithful reproduction, and a frame arrives every 30th of a second! This amount of data exceeds the memory capacity of most of the minicomputers that are responsible for the rapid influx of computer technology in so many other fields.

The second reason is the lack of algorithms or methods of processing this information that are rapid enough and "robust" enough for general use. The difficulty of building a fast algorithm is easy enough to understand in light of the huge amounts of data that must be processed for one image. The difficulty of building a robust algorithm is perhaps harder to understand for someone familiar with the tremendous successes of computers in other fields. (A computer program is called *robust* when it can work successfully in a wide variety of situations, as opposed to a few laboratory demonstrations.) Most people would con-

sider guiding a spaceship to a precise landing on the moon far more difficult than identifying a pencil in a photograph of a cluttered desk. The very opposite is true. The moon landing problem can be reduced to very precise equations. These equations are well suited to the numerical orientation of computers in existence today, and can be programmed and solved rapidly. By contrast, no programming language today contains a statement like "find the pencil" or even "look for something long and skinny, with a sharp point at one end and a pink lump at the other." The human brain, which finds the moon landing problem challenging, has evolved over billions of years to be extremely adept at finding pencils on tables.*

The SRI Algorithm

A major breakthrough in the field of machine vision took place in 1974 when Gerald Agin and R. O. Duda [1,2] of Stanford Research Institute developed an algorithm for a simple version of the vision problem that provided useful answers in many situations, and was at the same time robust and efficient to compute.

The inherent difficulty of the vision problem is illustrated by how many simplifying assumptions were necessary to make the SRI algorithm work. To begin with, the algorithm assumes that the picture has been reduced to a very simple form—called a binary image. This reduction, which is done either by high contrast lighting or by some other—as yet unperfected—preprocessing technique presents the picture to the computer in the following simple form: The picture is stored as an array of dots or pixels (short for picture elements) which are either on or off (1 or 0). The 1 pixels represent the object while the 0 pixels represent the background. Thus, in order for the algorithms to work at all, useful information about the object must be entirely represented by the object's silhouette. (A sample binary image as seen by the computer is shown in Figure 1.) Of course no color information is understood; but, in addition, information that might be derived from texture, shading or three-dimensional perspective is also lost. The algorithm further requires that the object be entirely contained within the field of view of the camera, and, if more than one object is in the field of view, they may not overlap.

Given all these restrictions, it is surprising that this algorithm is any more than a laboratory curiosity. Yet, its power derives from its success in meeting the two criteria mentioned above that have defeated other vision algorithms in the past. It is fast and it is robust, in that it can operate on any image meeting the above specificiatons. In addition, the algorithm is easy to use, and the information it provides is useful in a wide variety of industrial circumstances. In terms of speed, the simplicity and deterministic nature of the algorithm, together with recent advances in microcomputers, allow operating rates of six images per second or more. In terms of useful information, the SRI algorithm can reliably report on the position and orientation of an object, and such fundamental properties of an object as its area, moments of inertia, perimeter, ratio of perimeter to area (a measure of irregularity), maximum radius and a variety of other powerful geometric invariants. Furthermore, the algorithm will produce these invariants repeatably and reliably for a wide variety of objects and conditions. Its one principal drawback is the need to reduce information to a binary image, which generally requires high contrast lighting and a carefully structured viewing area.

One important aspect of the SRI algorithm is ease of use. The key parameters about an object are entered into the computer by a simple training operation. The object is shown to the camera in several positions and the computer statistically accumulates all the information it needs. This process, called training, can be carried out in a matter of a few minutes by an unskilled operator.

Much further research has gone into the SRI algorithm

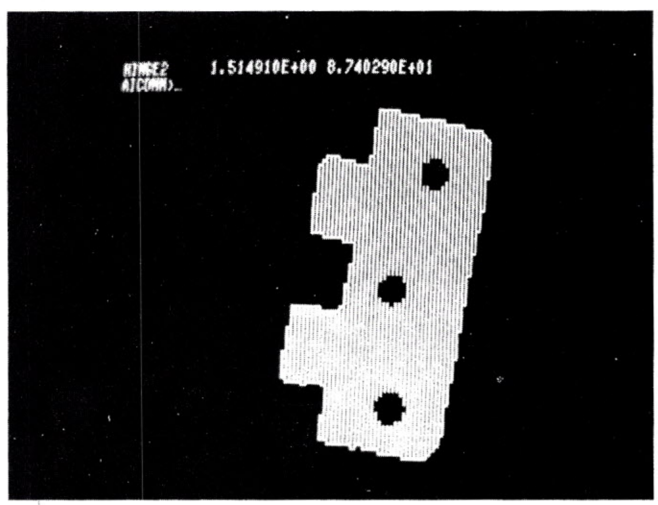

Figure 1. A binary silhouette image of a door hinge part, as seen by the computer.

*Editor's note: For a survey of robot vision methods and current research, see the article "Introduction to Robot Vision," in *Robotics Age*, Vol. 1, No. 1, Summer 1979.

since 1974, principally by the Vison Group at Stanford Research Institute, to further perfect this algorithm and remove some of the limitations. [3,4]

One thing the original SRI algorithm did not do is handle shades of gray in an image. If, instead of storing one bit of information per picture element, there was provision for storing 4 bits per pixel, these bits could be interpreted as a binary number representing 16 different levels of light intensity or gray tone. While hardware capable of converting video signals to gray scale and storing them has been available for some time, processing hardware that is fast enough and algorithms that are robust and general purpose have been scarce. [5]

Automatix Enters the Vision Scene

In the introduction of new technology to industrial use, the successful completion of a research project is only the beginning. The performance of the algorithm must be improved to where it can operate at the rates encountered in factory situations. It must be installed on a computer that can survive in the factory environment and work reliably for years with a minimum of maintenance. Training, applications support and repair service must be provided. The very largest corporations, with their own research laboratories, are sometimes able to bring new technology from the laboratory to the factory floor by their own efforts. Most companies, however, do not have the specialized resources to do this, and for them the adoption of new technology is strongly dependent on the availability of reliable commercial vendors.

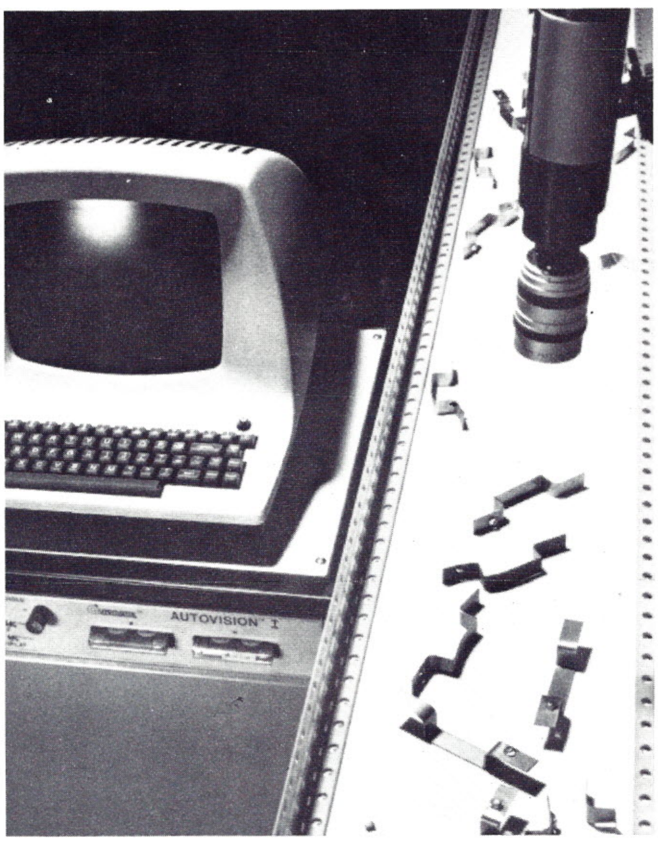

Figure 2. The Autovision system, consisting of a TV camera, processor, and control console, shown in a typical application.

Automatix Incorporated (AI), formed in January 1980 by a group with extensive experience in robotics, minicomputers and CAD/CAM technology, has as its charter the commercialization of advanced robotic technology in the form of complete modular "systems." AI believes that vision technology, as represented by the SRI algorithm and a number of its recent developments, is ready for such commercialization. The first AI product is a system called Autovision™(Figure 2). It is a vision module that combines the SRI-developed vision technology with the latest 32-bit microprocessor design, industrial packaging, advanced digital camera technology, and specific applications software. The SRI vision software serves as a nucleus around which further innovations—developed at AI and elsewhere—will be integrated with advanced concepts in robotic control. [6,7]

The Makeup of a Vision Module

For an advanced computer-based product like a vision module to be industrially viable, its manufacturer must provide three critical elements: hardware, software, and services. Of the three, hardware is probably the most tangible. In the case of the vision module the hardware may be further subdivided into five major subsystems: the camera, the vision preprocessor, the computer, the factory interfaces, and the enclosure. (A block diagram of the AI Autovision System is shown in Figure 3).

In its simplest form, the camera system is nothing more than an ordinary closed-circuit vidicon television camera of the type widely used for surveillance and videotaping. Such cameras are available from many manufacturers along with a large number of accessories, including lens, iris, mounting system and rugged enclosure. For many purposes such vidicon-based cameras are perfectly adequate. Where precisely repeatable measurements are necessary, however, vidicons have some drawbacks.

Because they scan a photosensitive surface with an electronically deflected electron beam, vidicons are sensitive to small changes in the deflection signals, causing a distortion of the picture. While this distortion is not bothersome to a human viewer, it can cause as much as a 10% error if measurements are made from the image, particularly at points near the outer edges. Recently, integrated circuit engineers have developed arrays of photosensitive cells on a single integrated circuit that can be scanned by digital means. Cameras based on such chips are commercially available and are smaller, more accurate and more rugged than the vidicon-based system. Because of the difficulty of building integrated circuits with hundreds of thousands of elements, all perfect, such cameras are also substantially more expensive.

One major aspect of the camera subsystem is the lighting, which can be a key factor in the success of a vision application. A variety of lighting techniques have been employed successfully in various industrial vision applications. Specific lighting system recommendations are extremely application dependent.

The second major subsystem in a vision module is the video preprocessor. The enormous amount of data contained in a digital camera image can easily swamp even the largest computer. Using high-speed dedicated electronics to carry out processing steps that reduce this data to a more manageable amount therefore makes sense. On the other hand, if the electronics is too carefully tuned to one particular algorithm it may not be usable on other algorithms, and the system will be unable to take advantage of future developments. A sensible compromise is to use advanced microprogramming techniques to build a vision preprocessor that can be adapted to a wide variety of algorithms. Such a microprogrammable preprocessor is one of the major advances in the Autovision II system from Automatix.

The Automatix vision preprocessor is also equipped to handle gray-scale images. Indeed, all images are acquired using the gray-scale process and the resulting image is thresholded to a binary picture under program control. This allows the program to try several different thresholds on the same image to get the best results. In addition, the microprogrammed arithmetic unit in the preprocessor can perform calculations on the gray-scale image, making normally ponderous gray scale algorithms more efficient.

Industrial Applications

What are some typical applications of this algorithm? Surely one of the most exciting is its use to guide heretofore blind robots. In almost all applications where robots are used today, the object must be in a precisely located, previously known position and orientation so that the robot can pick it up. If the object is displaced at all from the location, the robot will grasp at empty air or, even worse, damage the object or itself.

Needless to say, in many industrial applications objects are not accurately registered or fixtured ahead of time. In such cases a vision system must give the robot two pieces of information to pick up the object. First is the object's position. The SRI algorithm provides that information by computing the object's orientation. Here the situation is a bit more complex. For an object that is basically planar in nature, such as, say, a monkey wrench, a robot need only know the principal axis of the object. In the SRI algorithm this is determined by computing the axis of inertia. A more complex object might have several stable positions while lying on a work surface. Imagine a large hex nut, which might be lying hole vertical or horizontal. The SRI algorithm treats such objects by storing key information about each of the stable states and using its recognition capability to determine which of the stable states the object is in. Thus, the algorithm is able to tell the robot the object's position, its orientation and its stable state. The robot, in turn, would have separate programs for picking up the object in each of the several states.

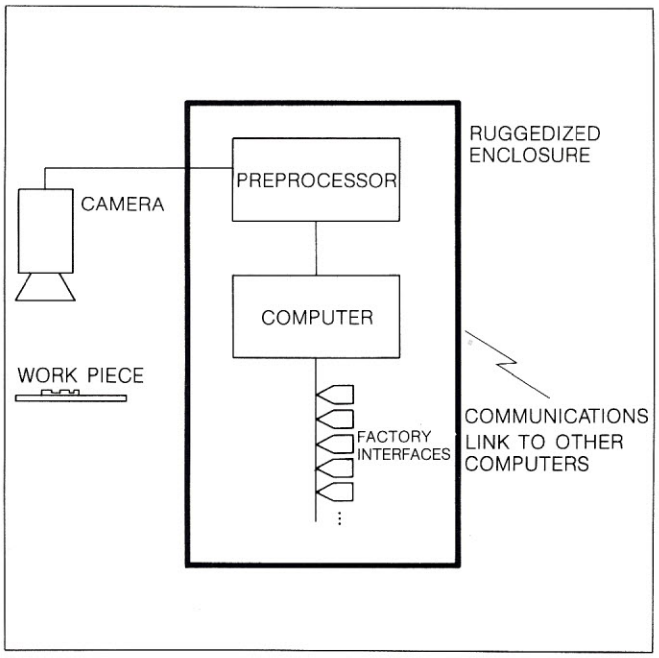

Figure 3. Autovision™ block diagram.

Inspection

Another major use of the SRI algorithm is sorting and part inspection. The geometric invariants calculated by the algorithm, in addition to providing direct information about the part, form a signature that helps distinguish different parts from each other. During the training process the algorithm automatically identifies the most useful sorting features or "discriminant" for a given set of parts.

Thus, if a number of different part types were coming down a conveyor belt, a vision module using the SRI algorithm could sort those parts into different bins—either by commanding a robot or by turning on or off diverter vanes or blasts of air. Perhaps of wider importance is the ability to distinguish good parts from bad. In many processes it is important to know whether all manufacturing operations have taken place successfully. A mounting plate, for example, might have a number of holes, brackets, and studs, each created by a different operation. One hundred percent inspection of such mounting plates by a vision system could avoid costly rework when an installed defective mounting plate has to be replaced. Another example is injection molding, where an inadequate plastic charge can result in misshappen features that can be recognized by the vision module. One thing the algorithm is not capable of is very high-precision measurement. Precision machined parts must often be inspected to better than one-tenth of the manufacturing tolerance—often a tenth of a mil (0.0025 mm). Such problems await other solutions.

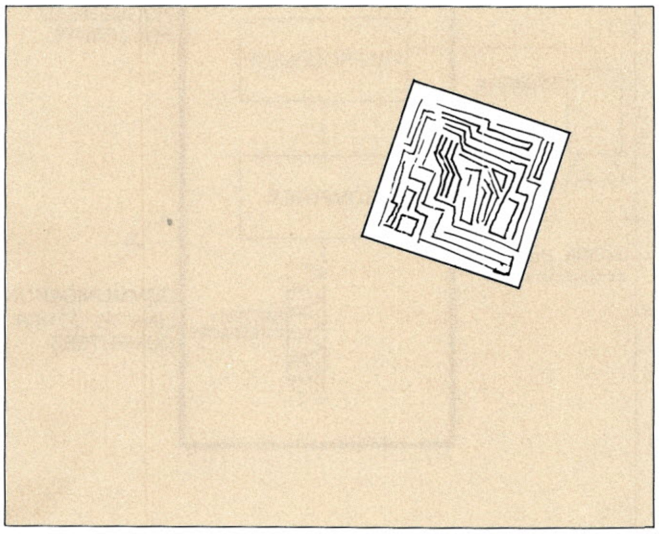

Figure 4. An illustration of a typical inspection task.

The Computer

The third subsystem in a vision module is the central computer. No other part of the system has been so profoundly affected by the enormous advances in solid-state technology. The first microcomputers, introduced less than a decade ago were 4-bit systems. While these were, and still are, used to replace complex special-purpose logic in a wide variety of applications, it was only with the introduction of 8-bit devices that microprocessors took on the flavor of real computers, with operating systems, higher-level languages, and mass storage. Sixteen-bit microprocessors have been recently introduced and are meeting with wide success. However, Automatix has chosen to use the most advanced microprocessors, with 32-bit internal design, in Autovision. Automatix felt that the large processor requirements represented by vision processing, robot control and other demanding factory tasks require the very best in microcomputer performance. Not only does such a microprocessor offer very high processing speeds but its wide address architecture permits the marshalling of large amounts of high-speed memory to further improve system performance. Therefore, application development at AI should not be computer limited.

The fourth key subsystem is the industrial interface. No matter how clever or efficient the vision system is, it does no good unless it is able to affect other operations in the factory. In addition, the vision process itself must be synchronized with other processes. Finally, the vision system may have to coordinate with other computers in an integrated factory information system. Autovision meets these needs by providing discrete opto-isolated signal lines that can be used to drive solenoids, relays and motors and to sense signal levels and contact closures in coordinated machinery. It also provides serial and parallel interfaces to other computers.

The final key subsystem is an enclosure that can protect the sophisticated electronics of the vision module from various hazards, including the dust, fumes and temperature extremes often encountered in factories. At the same time the total package must facilitate reliable operation and rapid restart in the event of external power failures. The Autovision System cabinet is being designed to meet NEMA 12 standards, thus assuring suitability for installation in most factories.

Software

Of the three major elements of a viable vision product—

hardware, software, and service—software is the most complex and intricate, and, if not done properly, can be the most obscure and error-prone component. It has become a cliché that sofware costs are increasing at the same time hardware costs are decreasing. Perhaps one reason is that hardware people tend to adopt new technologies universally while software continues to cling to old methods. No engineer today would design with 10-year-old chips, yet the most popular software tools and languages of today were developed in the vacuum tube era. The persistence of obsolete techniques, such as writing entire systems in assembly language, is in part due to the limited memory capacities of 8- and 16-bit microcomputers. Automatix has chosen to base its software development on a modern well-structured high-level language in widespread use, namely Pascal. Selected critical performance subroutines are rewritten in assembly language to assure high-speed execution once they have been debugged in Pascal. These routines usually comprise less than 5% of the total code.

It is uncommon for the largest engineering investment in a product such as Autovision to be in the software area. Most companies, including Automatix, consider the details of their software to be valuable trade secrets and guard them closely. However, some potential users of advanced systems will need to modify or expand parts of the software to work in special circumstances. Automatix has taken the unusual step of providing arrangements whereby customers may have access to the Autovision source code upon signing necessary licensing and trade secret protection agreements.

An Application Language—RAIL™

Modifying the Pascal software programs would be undesirable for most customers, however, since modifications require a computer programmer and incur some risks of introducing system errors. By giving a user without special training in computers an easy way to tell the vision module what actions it should take under various circumstances, and what criteria it should use in processing images, much of the need for system modification can be avoided. Automatix provides this capability with a simple yet powerful and flexible language called RAIL™ (Robot Automatix Incorporated Language). RAIL makes it possible to sequence the operations of the Autovision System so that the desired task is performed.

The flexibility and power of RAIL are illustrated by the example inspection task shown in Figure 4. The shaded rectangular region represents a heat sink and the smaller square represents an I.C. chip that has been bonded to it. If the chip is not too close to the edge of the heat sink, and is not tilted too much, the assembly is a good one. This example is motivated by an actual inspection task described in [8] and in [9].

The RAIL program for this inspection task is shown in Figure 5. We assume that the parts are moving down a conveyor and that there is a part detector which signals when a part comes into view. After declaring I/O ports for the conveyor-running sensor, part detector, and part-reject solenoid, the program asks the user for tolerances for the chip offset and the chip orientation. It then waits until the conveyor is on, and, while it remains on, processes each part that comes into view.

The actual inspection procedure is entirely contained in the single IF-THEN-ELSE statement. It simply states that if the difference between the maximum X-values of the heat sink and the chip (which are the rightmost points on the boundary of the respective components in Figure 4) is greater than or equal to the offset tolerances, and if the orientation of the chip is within the specified tolerance of 90°, then the part is good—otherwise, it is bad. The striking similarity between the RAIL code and the manner in which the inspection procedure might be described in English illustrates both the power and the simplicity of RAIL.

```
INPUT PORT 1 : CONVEYOR
INPUT PORT 2 : PART_DETECTOR
OUTPUT PORT 1 : BAD_PART
WRITE "ENTER CHIP OFFSET TOLERANCE: "
READ OFFSET_TOL
WRITE "ENTER CHIP TILT TOLERANCE: "
READ TILT_TOL
WAIT UNTIL CONVEYOR = ON
WHILE CONVEYOR = ON DO
 BEGIN
    WAIT UNITL PART_DETECTOR = ON
 PICTURE
 IF XMAX ("HEAT SINK") - XMAX ("CHIP")> = OFFSET TOL
         AND
    ORIENT ("CHIP") WITHIN TILT_TOL OF 90
    THEN
       BAD_PART - OFF
    ELSE
       BAD_PART - ON
  END
```

Figure 5. The RAIL™ program for the example inspection task of Figure 4.

XMAX and ORIENT are features calculated in software. RAIL can reference any feature of any component of the picture, simply by stating the name of that feature along with the name, assigned during training, of the desired component. This is extremely powerful because it allows for the use of any feature in either an arithmetic or logical expression. Additional capabilities of RAIL will make it possible to write programs to control robots and to integrate sensors with robots.

Services and Product Support

To guarantee the success of a high-technology application such as a vision system in the demanding environment of a factory, the potential user of such a product must evaluate the full range of services provided by its supplier. These include pre-installation applications support, thorough user training, documentation, spare parts, and field service support. No factory can tolerate frequent breakdowns by any piece of equipment that can stop the production line. Many customers will first choose to place one unit in a manufacturing development laboratory, where it may be supplied with periodic software updates reflecting advances in the state-of-the-art of vision processing technology in order to advise the factory on promising applications. The system must also be able to coordinate with other advanced technologies such as robots.

In addition to these features and services, a key element of the Autovision system's "Availability Assurance" program is the inclusion of thorough self-test diagnostics that permit rapid correction of problems by on-site user personnel using only basic electrical maintenance techniques such as module switching.

Conclusion

Early work in vision research, particularly the development of the SRI algorithms along with large scale improvements in microprocessor technology, has brought vision technology to a plateau from which practical industrial vision systems for inspection and robot control can be developed and successfully applied.

Automatix, along with other companies in the field, will deliver vision systems in 1980 as modules for use in inspection and in sensor controlled robot systems. Application software, fast image processing and extensive user support are required for commercial success. However, there is no doubt that in the decade of the 80's, the introduction of vision systems and other sensor modules will revolutionize factory automation.

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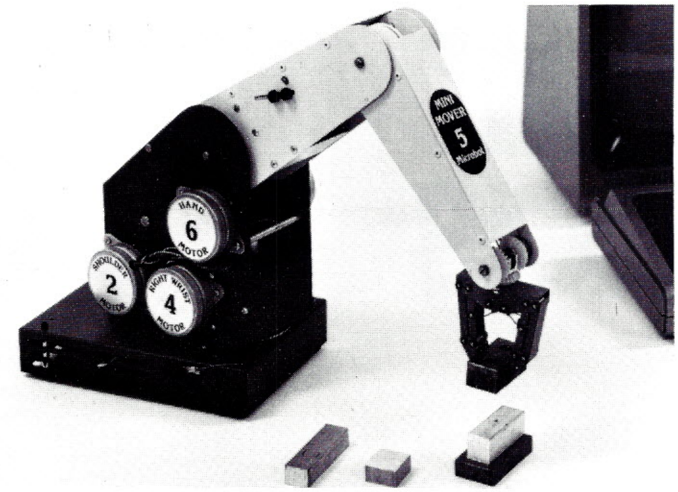

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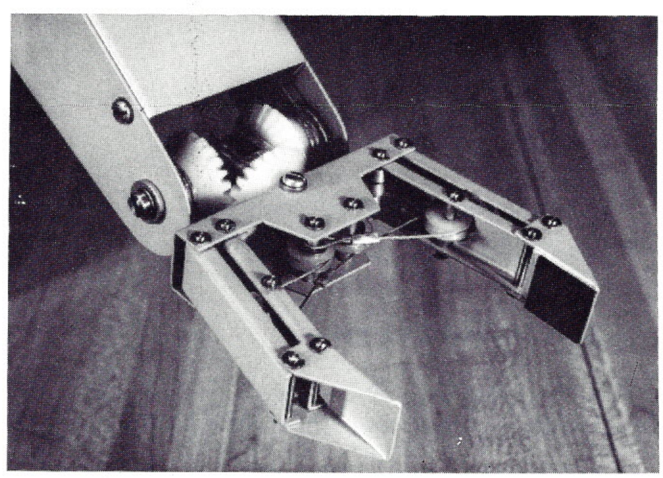

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INDUSTRIAL ROBOTICS '80

The 10th International Symposium on Industrial Robots and the 5th International Conference on Industrial Robot Technology were held jointly in Milan, Italy. Robot manufacturers, researchers, designers, engineers and users from countries large and small gathered in Milan this spring to compare notes, present papers and review the rapidly changing state-of-the-art.

While well attended by American representatives of robotics technology, the conference was dominated by Europeans. The 61 papers presented at the conference were testimony to the rapid growth and significant new developments in this exciting emerging technology.

Presentations were grouped in the following categories:

- Applications and Processes
- Computer Controls
- Robot Vision Systems
- Grippers
- Handling Applications
- Automatic Control
- Visual Pattern Recognition
- Systems Applications
- Robot Mechanics
- Robot Assembly
- Tactile Sensing
- Social and Economic Aspects
- Commercial Products

This article covers a brief description of one or more of the papers presented in each category.

Applications and Processes

The first session of the symposium dealt with robot applications and processes. Five papers presented centered on industrial applications covering ring forging, multipass welding, continuous path welding and automotive spray painting. The opening paper of the session described the utilization of a robot system on the solid rocket booster components for the NASA space shuttle program.

The application of a sprayable ablative compound to meet thermal protection requirements on large segments of solid rocket booster components was accomplished rapidly and economically by a computerized robot system developed by United States Booster, Inc. (USBI), a space shuttle program subcontractor to NASA.

The paper presented at the symposium described the robot spray system, application parameters and special techniques used to accomplish the task at the Kennedy Space Center.

The sprayable ablative material is an epoxy-terminated urethane resin filled with organic as well as inorganic ingredients.

The major problems in apllying the Thermal Protection System (TPS) materials involved development of a spray system which could 1) control material thickness to close tolerances, 2) duplicate hand spray gun techniques on both large and small structures, and 3) be able to apply the sprayable material rapidly and economically.

A special problem centered on the fact that in addition to the flight ascent phase, the solid rocket booster (SRB) requires thermal protection through re-entry. Also, the material must maintain its effectiveness over the useful life of the structure (estimated at 20 flights) and be amenable to periodic refurbishment on a cost-effective basis.

A DeVilbiss/Trallfa robot spray system was purchased to serve as the main element of the work cell. Robot movements are affected by hydraulic cylinders and rotary motors controlled by a combination of servo-valves and position-measuring systems using potentiometers and resolvers. Each linear cylinder and rotary motor has its

own valve and measuring system tied to the memory "teaching" and control unit.

Positional signals are recorded as sequential digital information from the manipulator as it is led through the desired moves. Sampling and recording rate of discrete bits of position information occurs at the rate of 80 times per second. During playback, the recorded position information is constantly compared (electronically) to the actual position of the cylinders and rotary motors and used to produce the joint movement signals.

Three linear sweep cylinders are used for manipulator arm movement giving a 93° sweep from side to side. The flexi-arm utilizes the operational end of the arm. It is a round, flexible extension made up of several "gimbal" joints allowing it to articulate and incline freely in any direction.

Joint assembly resembles "universal joints" but include two high-precision hemispheres with intermeshing pins and holes. In any position a large number of pins are engaged in the holes, giving good stability. Three joints are connected in-line and driven by a pair of linear cylinders, each connected to an off-axis point. A third rotary hydraulic motor rotates the tool carrying point. The extension, 4 inches in diameter and 14 inches long, affords easy movement in tight work areas.

The program capacity of the robot is 64 minutes, and the system can be synchronized with a conveyor for automatic control of playback rate. Programs may be edited or entire diskettes copied. The system calculates remaining program capacity and a diagnostic LED display assists the operator in troubleshooting.

Point-to-point robot control was chosen over the continuous path method, which involves the continuous recording of information at a given sampling rate. In point-to-point mode, the operator moves the manipulator through the program, recording time and position information at his discretion, permitting longer stored programs. On playback, the microprocessor interpolates linearly between spotted positions and the manipulator moves smoothly through the motions.

The other work cell component is a low-profile turntable floating on a frictionless film of air, which can be rotated manually or by a drive unit for spray application on cylindrical shapes. Turntable and robot control are integrated, allowing the preprogramming of turntable commands into robot spray motion movements.

The robot manipulator unit is supported and moved by a hydraulic scissor lift platform, extending its normal operating range. Lift drive is also interfaced with robot control. A portable "teach" platform attaches to the lift platform during the programming mode.

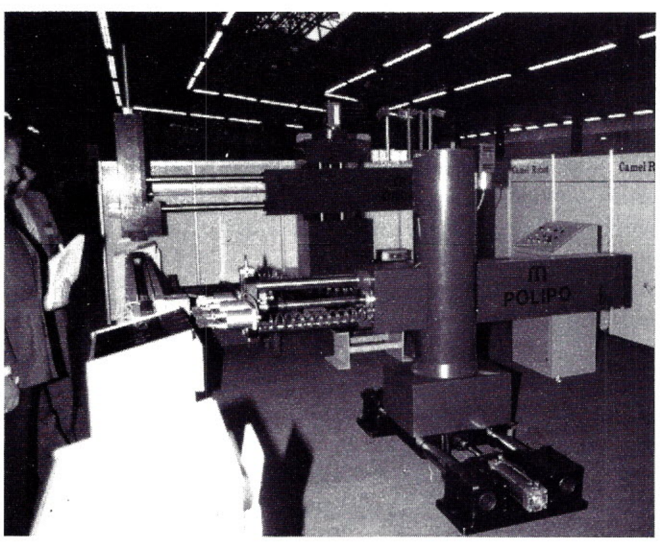

Figure 1. The Italian-made "Camel" robot.

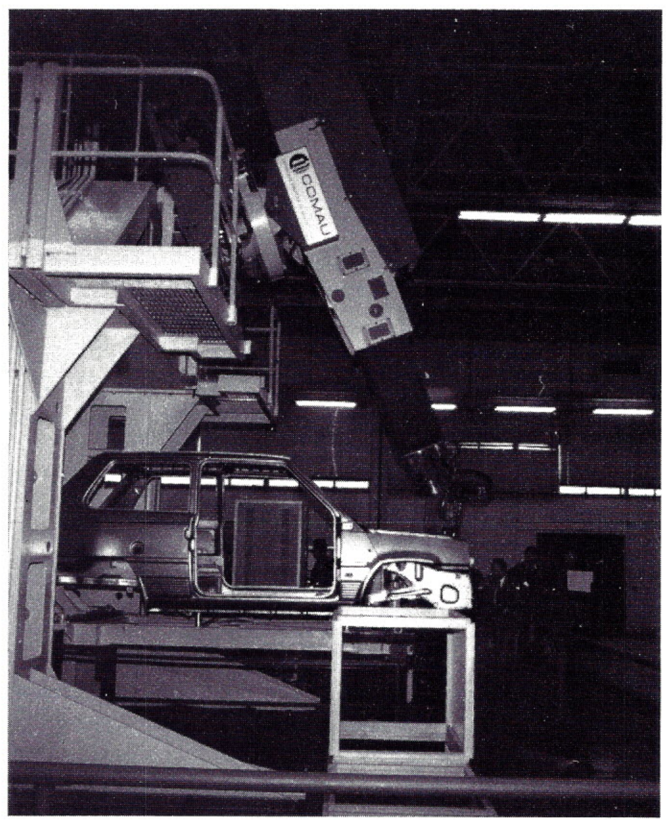

Figure 2. The "Robogate" welding robot, built by Comau for Fiat.

The robot system was successfully tested and satisfied all design parameters. USBI engineers set up a full scale manufacturing process plant in the vehicle assembly building at Kennedy Space Center.

Computer Controls

Five papers presented at the symposium dealt with computer control techniques involving development of software systems for controlling industrial assembly robots, user-defined control structures in robot programming languages, program abstraction and error correction, off-line programming, and a microcomputer-based stepping motor driver. A sixth paper covered an update of the AL manipulator programming system developed by the Stanford Artificial Intelligence Laboratory.

A paper on "Distributed Robot Programming" outlined the design and development principles of an integrated software system implemented around the Supersigma robot of the Artificial Intelligence Program at Milan Polytechnic. The software system is oriented toward automation of mechanical assembly tasks in which the robot must manage complex functional activities and allow interaction between the operator, sensors, and motors, as well as communicate status information.

The system is divided into three levels of hardware and software. The paper deals with the intermediate level or interface progam between a high-level manipulation language and microprocessor network directly controlling the mechanical devices.

A paper investigating the impact of studies covering user-definible control structures on the design of robot programming languages was also presented. Its main thrust was the development of flexible control structures in language as a workable and effective tool for robot programming, especially as it applies to the definition and management of high-level control mechanisms.

The paper proposed the application of DIL, a system designed for supporting user definition and implementation of control structures, in robot programming languages. It opened, however, with a definition of MAL (multipurpose assembly language), in which the user can define, by means of simple declarations and rules, control structures tailored to his own application.

The current status of the AL manipulator programming system, in operation at the Stanford Artificial Intelligence Laboratory, was noted in a paper that was basically an update of the first user AL programs written in 1975. AL is a high level manipulator programming language utilizing concepts of structured programming, permitting manipulator tasks to be coded similar to the way algorithms are coded in block-structured, high-level algebraic languages such as ALGOL or SAIL.

Ongoing work at Stanford involves a library of predefined assembly operations that permit programs to be written in terms of assembly elements and allow the user to specify action on objects and coordinate frames, rather than in terms of motion statements.

Robot Vision Systems

Four papers dealing with various vision system applications were presented at the symposium. The first covered a computer vision and part-feeding system developed by SRI International that determines the stable state, location and orientation of randomly oriented parts (up to 150 mm in length) and places them in a desired orientation.

SRI's approach is directed at feeding parts for programmable assembly sytems currently under development. In such systems a robot picks up parts from different feeding stations and assembles them into a product. The overall task is greatly simplified if individual feeding stations can present parts in a predetermined position oriented for proper gripping and insertion. The desired cycle time for the SRI system is one to four parts per minute.

The other papers covered visual identification and sorting with a TV camera, applied to automated inspection apparatus, a color sensing system that recognizes ten distinct colors as well as color variations within the group of ten, and a Kawasaki vision system applied to path correction for arc welding.

Grippers

The majority of workpieces used in industry are stored in containers (bins). In many operations, machines must be loaded with workpieces taken from such containers. Four papers covering the development of various types of grippers to automate machine loading tasks were also presented.

The first covered experiments performed using a surface adapting vacuum gripper to acquire a variety of randomly oriented workpieces from a bin. The paper outlined the problems encountered with a gripper of this type and an approach to solving such problems with a contour adapting gripper.

Other papers covered the development of a prehension system for grasping workpieces of a generic shape, general discussion of new systems for recognition and positioning of mechanical parts, and study and experimentation with a

multi-finger gripper able to catch objects of any shape without damaging them, even if they are fragile.

Handling

Six papers covering handling applications were presented. Among them were "Integrated Manufacturing Systems in the Swedish Automotive Industry," "Industrial Robots in the Flexible Manufacturing Systems of the Coach Building Industry in Hungary," "Automation of Multitransitional Sheet Stamping of Large Parts with Industrial Robots in the USSR," a description of a robot for conveyor loading and unloading, and a paper discussing the design of a computer controlled manufacturing cell consisting of an industrial robot surrounded by three machine tools, with the robot transporting workpieces between the machine tools and stock.

A paper on industrial robots in advanced production systems described newly developed features of the ASEA IRB robot system that make it feasible to automate small batch production by the use of robots. The new features include adaptivity, extended external memory and computer interfacing.

A practical application of the ASEA robot was described wherein it serves a machine cell used for drilling printed circuit boards. The automatic system consists of a supervisory computer (MODCOMP II), two drilling machines (EXCELLON XL3), one ASEA IRB-60 robot, one ASEA DS820 process data terminal, and a number of part-feeding magazines.

Automatic Control

Effective robot operation in a manufacturing environment depends on robot control systems possessing measurement and sensory capabilities. A paper presenting a model for such a system, entitled "A Measurement and Control Model for Adaptive Robots," was presented at this year's symposium.

Parallel control and measurement hierarchies were considered in the article. Control divides the work routine into tasks and subtasks, while measurement analyzesdata from sensors. At each level, control sends expectations to the measuring hierarchy, which returns computed values of the deviation between observed and expected data. The control hierarchy modifies task strategies based on this input to generate sensory-interactive, goal-directed behaviour.

The inherent advantage of hierarchical control is that complexity at any level in the hierarchy can be held within manageable limits irrespective of the overall complexity of the structure.

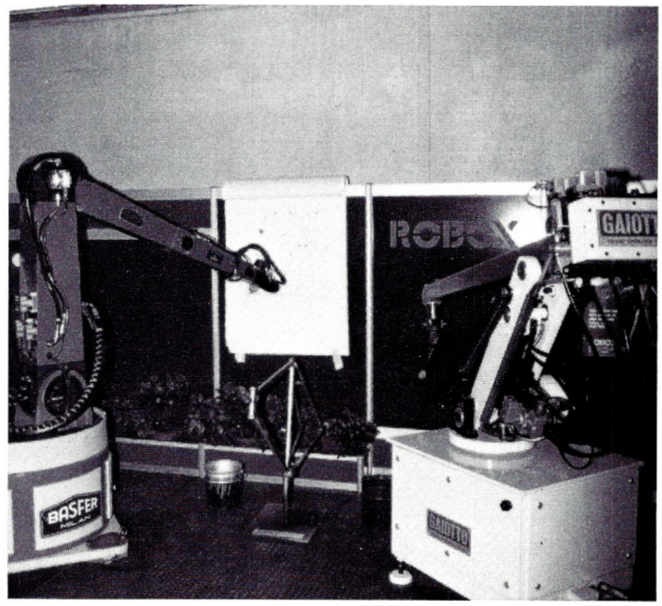

Figure 3. Painting robots made by the Italian firms Basfer and Gaiotto.

Research at the National Bureau of Standards into methods for designing and implementing real-time sensory and control functions in the structure is in progress. Work is also being conducted on the development of engineering procedures for partitioning major tasks into subtasks, assigning tasks to logical modules, designing hardware to implement this logic, and writing software.

The system has been partially implemented on a research robot using a network of microcomputers and a real-time vision system mounted on the robot's wrist.

"Precision Measurement by Stereovision System" was the subject of a paper presented by the Istituto di Elettrotecnica ed Elettronica, Politecnico di Milano, Italy. The paper provided a conceptual framework for stereo vision and investigated error introduced by stereo measurement using low-resolution cameras. Attention was focused on fundamental problems encountered during interpretations of images, rather than on specific applications.

A complete algorithm was given for the interpretation fo a "binary" represented by a pattern of 0's and 1's. The method was fairly accurate in describing the topology of the image in the form of a planar graph.

Robot Assembly

A paper entitled "Matching the Assembly Robot with the Factory" described five years' experience in tooling a general purpose system based on the Olivetti SIGMA robot.

Figure 4. A welding system by Hall Automation (U.K.), featuring automated turntable and fixturing.

The paper covered early industrial applications of SIGMA as well as future trends, software and language problems encountered, cost, quality, and the impact of the introduction of robots into factory assembly operations.

The paper called for a joint effort on the part of robot designers and users to consider the entire functional structure of robotics applications in the interest of establishing the necessary peripheral support and operational safety.

Additional papers covering social and economic aspects of robot application included "Methodology of Economic Efficiency Evaluation of Industrial Robot Applications in Poland," "Social Conditions and Consequences of the Use of Industrial Robots in Five Factories," and "Use of Industrial Robots and Manipulators in Plants."

Tactile Sensing

A paper presented by Charles Stark Draper Laboratory, Inc., USA, described Remote Center Compliance (RCC), a simple passive device for aiding close-clearance insertions that has proved to be a valuable addition to robotic machines and fixed assembly stations. RCC development is based on the concept of sensing physical information from the interface of mating parts and using that information to adapt the motion of parts to the assembly task.

In applications where there is a need for feedback from the assembly interface (and for technical reasons, force measurement is not ideal for providing this feedback), monitoring the state of RCC displacement provides a satisfactory feedback vector.

The combination of RCC technology and the technology of sensing for feedback was described in the paper. Displacement-monitored RCC applications include the teaching of robot moves, updating geometric data bases, correction of robot drift and other non-stationary effects, go/no-go gauging, family or individual error measurement, and inspection or documentation.

Commercial Products

The decreasing cost of microprocessors has led to the development of more flexible, sophisticated and powerful control systems for robots. A paper entitled "New Ideas in Multi-Task Real-Time Control System for Industrial Robots" describes a multi-task real-time control system based on a common 8-bit microprocessor.

The most evident advantage of multi-task real-time control is flexibility. One control system can control several robots independently at the same time. The program system is modular; new functions can be included by introducing new program modules.

The principal idea introduced by the paper focuses attention of the servicing of machine tools and not on the industrial robot servicing them. By defining the servicing of the tool as a task and the robot as a resource, neither the robot nor the other machine tools it serves need be tied up if one machine tool stops.

Award Presentation

On the first night of the conference a dinner was held at the Milan fairground, where the 1980 Joseph F. Engelberger award was presented to Richard E. Hohn of Cincinnati Milacron for his outstanding contributions to robotics technology. Hohn, product manager of Cincinnati Milacron's robot division, was given the award for his development of control systems and programming used in Milacron's T3 robot. Hohn has been awarded a number of patents as a result of his work with servocontrol systems on the robot.

The 11th International Symposium on Industrial Robots will be held in October 1981 at Keidanren Hall, in Tokyo, Japan. Based on the growing attendance and the number of technical papers presented, the 11th I.S.I.R. should top all previous records in this growing industry.

Robots on your own time

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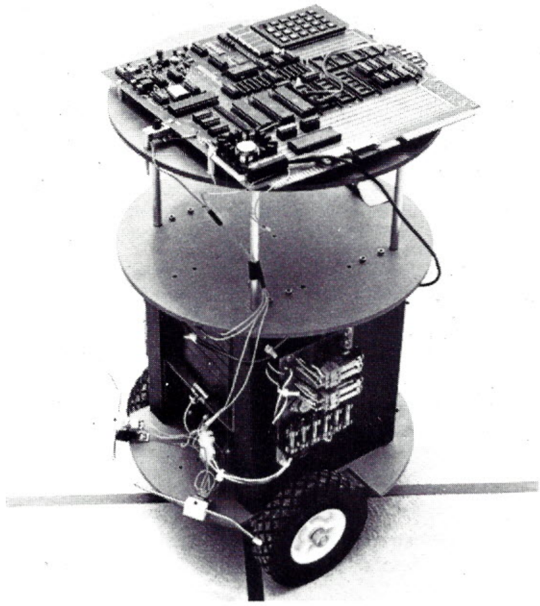
SUPERKIM Meets ET-2



This article presents some of my experiences in interfacing and programming a SUPER-KIM single board computer (SBC) for the control of a Lour Control ET-2 robot shell (Figure 1). The ET-2 (*E*xperimental *T*ransmobile with *2* drive motors) consists of a three level frame powered by two separately driven wheels and balanced by a free caster. The lower level contains the drive motors and gearbox, a 32 amp-hour 12V motocycle battery, and two driver electronics boards. The upper levels are available for the installation of user equipment. In this case, the SBC is mounted on top.

The ET-2 may be operated under computer control using only four TTL command lines. Each motor has two control bits, one to turn it on and another to set its direction (by a reversing relay). The driver boards provide the amplification necessary to convert from TTL logic levels to the 12 volt power for the motors and relays. Control of motor speed is obtained by varying the duty cycle (the percentage of time the bit is on) of a low frequency (10-20Hz) square wave signal applied to the motor's drive bit. The inertia of the motor and robot effectively average the signal to a proportionally lower DC level at the motor.

The drive motors are Ford permanent magnet windshield-wiper motors, which, besides having built-in gear reduction that produces a good deal of torque, are also less expensive than PM motors with comparable performance and are readily obtainable. Each motor can be independently driven in the forward or reverse direction. Lour states that to turn the shell, the preferred method is to drive one motor forward and the other in reverse so that the robot spins on its vertical axis. Turns with only one motor driving are not recommended, due to the increased loading of the motor. Reversing a motor while it is in operation can put a tremendous strain on the motors and drive system. Thus, both motors should be programmed to stop briefly between commands.

The SUPERKIM, by Microproducts, Inc. is a complete, powerful microcomputer control system based on the 6502 microprocessor, contained on a single 11.5 x 11.5 inch PC board. The board is fully socketed for easy servicing and expansion to 4Kbyte RAM and 16K EPROM on board. It

comes with 1K RAM, and the address space is fully decoded so that with additional boards up to 64K of memory or I/O may be used. For this purpose, the CPU bus lines are brought out on wire-wrap pins that may also be used with standard in-line ribbon cable connectors to expand the bus.

The SUPERKIM has eight priority interrupts which are individually vectored and resettable under software control—a feature useful for real-time robot control systems. Four SYNERTEK 6522 Versatile Interface Adapter (VIA) sockets are provided on the board; one 6522 comes with the board. This IC is indeed a very flexible I/O device, containing two bidirectional 8-bit parallel ports with handshaking (with each bit separately programmable for input or output), an 8-bit, bidirectional serial to parallel shift register, and two 16-bit programmable counter/timers. The board comes with a 6530 interface chip as well.

The ports on the 6522's could also be used for implementing analog to digital converters (ADC's). A full complement of 6522's would permit up to eight 8-bit ADC's for interfacing to robot sensors, etc.

Interfacing the SUPERKIM to the ET-2

The SUPERKIM is mounted to the topmost PVC platform on the ET-2 with machine screws and .75″ spacers. 12V from the battery is supplied to the SUPERKIM's on-board 5V regulator through a SPDT switch.

Figure 2 shows the location of the pins on the 6522 that are used as output ports to the ET-2. The four control lines of the ET-2, D1, D2, E1, E2, are connected to the control bits in the SUPERKIM's J5 VIA parallel output port as shown in Table 1. There are, of course, many alternate possibilities for configuring the interface. For convenience, the motor drive signals were assigned to bits 0 to 1 of port A (address 1302H) and the reversing relays to the corresponding bits of port B (address 1303H). Note that since the drivers on the ET-2 invert the logical sense of their inputs, a logical 0 (low) on an output will turn the corresponding motor or relay ON, and a logical 1 (high) will turn it OFF. Thus, writing to addressed 1302 and 1303 controls the motors and relays directly, with sixteen possible control states.

Due to the action of the power on reset, the I/O ports of the 6522 are initialized to be output ports, and zeroed. Therefore, as soon as the SUPERKIM is turned on, the ET-2 will lurch forward if the motor drivers are connected to the interface. To eliminate this problem, a 2-pole switch is used between the 6522 outputs and the motor drive inputs, which should be open when the computer is switched on. After location 1302H is set to 03, the motors may be engaged. The switch also comes in handy as a panic switch if your program causes the ET-2 to run amok!

Figures 3 and 4 show examples of ET-2 turning maneuvers. In Figure 3 the left motor is driven in reverse while the right motor runs forward, resulting in the preferred spin turn. In Figure 4 the right motor is driven forward with the left motor turned off, so that the left wheel is the axis of the turn, and the turn is more gradual. As mentioned above, the spin turn should be used for best results.

We will now describe how to reproduce these and more interesting movements using the SUPERKIM, both directly from the keyboard and then under program control.

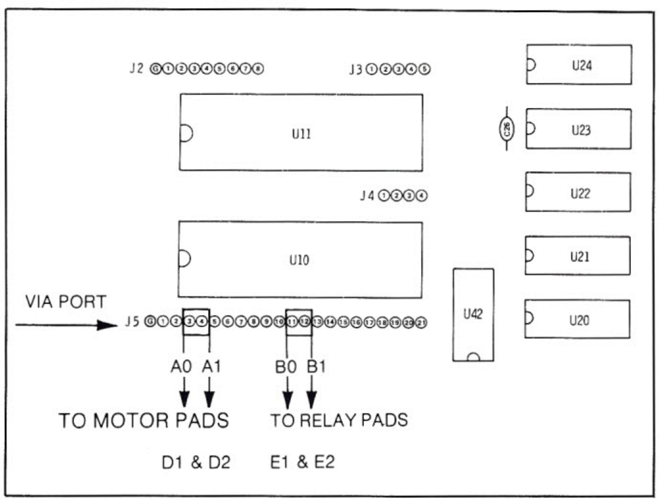


Figure 2. SuperKim/ET-2 robot control interface connections.

Direct Command Mode

With the SUPERKIM interfaced to the ET-2 as previously described, constant motion modes can be commanded

TABLE 1

CONTROL LINE	FUNCTION (WHEN LOW)	J5 PIN
D1	RIGHT MOTOR ON	PIN 3 (A0)
D2	LEFT MOTOR ON	PIN 4 (A1)
E1	REVERSE RIGHT	PIN 11 (B0)
E2	REVERSE LEFT	PIN 12 (B1)

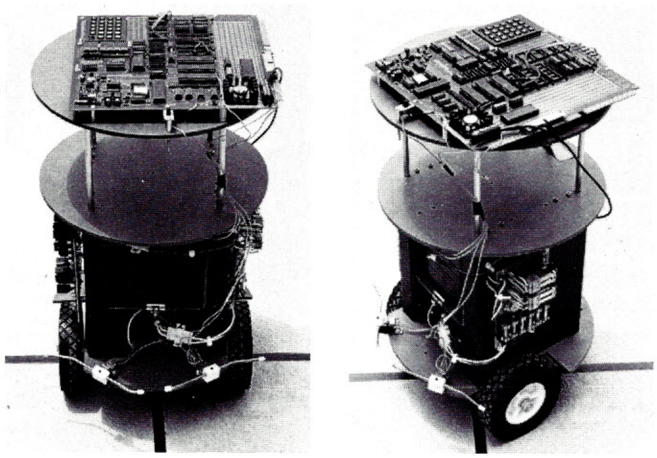


Figure 3. An on-axis turn. With one motor reversed, the ET-2 can turn in place.

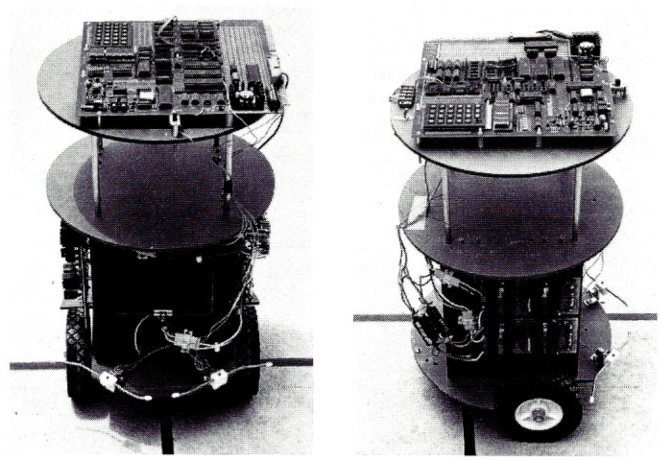


Figure 4. A "one-motor" turn. With one motor off, ET-2 turns with the stopped wheel as an axis.

directly from the keyboard as follows:

Step 1: Make sure that the motor switch is turned off (motor drivers disconnected from the computer) and then turn on the computer power switch. The display should light up.

Step 2: As described in the SUPERKIM manual, initialize the keyboard interrupt vectors as shown in Table 2. These values make the single step (SST) and stop (ST) keys work correctly.

Step 3: The ET-2 can now be commanded manually by entering the desired control states into address locations 1302H and 1303H. Table 3 shows the results of various output setings. *Note that the ET-2 should not be driven with both motors reversed, as the caster turns inwards and makes the unit unstable.*

Step 4: After the desired state is entered, turn the motor switch ON. *WARNING: In this mode the unit can only be stopped by turning the motor switch off, disconnecting the driver inputs from the computer!)*

Movement Under Program Control

While the direct command mode will allow you to check out your wiring, more complex sequences of control states must be commanded by machine language programming. Programs can be entered and debugged directly from the hexadecimal keypad on the SUPERKIM and then saved using the board's build-in cassette tape interface.

A highly desirable alternative to machine language programming is the use of a 6502 development system (APPLE, etc.). Instead of keying your program into memory in hex code, programs can be prepared on the development system using an assembler and then downloaded to the SUPERKIM through its serial interface. The advantages of using an automatic assembler to translate opcodes and compute the addresses for a new code file will become obvious the first time you have to add an instruction into the middle of an existing machine language procedure.

Table 4 is a listing of a 6502 machine language program for moving the ET-2 in a roughly octagonal pattern. It makes use of two nested time delay subroutines, LDELAY (long delay) at 0300H and SDELAY (short delay) at 0310H. SDELAY itself consists of two nested delay loops, each counting down from FFH to 0 (256 cycles) resulting in a delay of about 0.25 sec.

The byte at 0301H sets the loop count of the LDELAY subroutine, and is originally set to 2 as shown, for an aggregate delay of about half a second. Different delays may be obtained by using that byte as a subroutine parameter,

TABLE 2

ADDRESS	DATA
17FA	00
17FB	1C
17FE	00
17FF	1C

TABLE 3

ADDRESS	CONTENTS	CONTROL STATE
1302	00	BOTH MOTORS ON
	01	RIGHT MOTOR ON
	02	LEFT MOTOR ON
	03	BOTH MOTORS OFF
1303	00	BOTH RELAYS ON
	01	RIGHT RELAY ON
	02	LEFT RELAY ON
	03	BOTH RELAYS OFF

TABLE 4

ADDRESS	CONTENTS	LABEL	OPERATION	COMMENTS
0200	A9 03		LDA #$03	;POLYGON PROGRAM
0202	8D 03 13		STA $1303	;TURN RELAYS OFF
0205	A9 00	LOOP:	LDA #$00	
0207	8D 02 13		STA $1302	;BOTH MOTORS ON
020A	20 00 03		JSR LDELAY	;WAIT
020D	A9 03		LDA #$03	
020F	8D 02 13		STA $1302	;BOTH MOTORS OFF
0212	20 00 03		JSR LDELAY	;WAIT
0215	A9 01		LDA #$01	
0217	8D 02 13		STA $1302	;RIGHT MOTOR ON
021A	20 00 03		JSR LDELAY	;WAIT
021D	A9 03		LDA #$03	
021F	8D 02 13		STA $1302	;BOTH MOTORS OFF
0222	20 00 03		JSR LDELAY	;WAIT
0225	4C 00 02		JMP LOOP	;KEEP ON GOING
		;		
0300	A0 02	LDELAY:	LDY #$02	;SET DEFAULT COUNT
0302	8C 20 03	LOOP1:	STY COUNT	;SAVE IT
0305	20 10 03		JSR SDELAY	;CALL SHORT DELAY
0308	AC 20 03		LDY COUNT	;GET COUNT
030B	88		DEY	;COUNT DOWN 1
030C	D0 F4		BNE LOOP1	;CONTINUE TIL ZERO
030E	60		RTS	;RETURN
		;		
0310	A2 FF	SDELAY:	LDX #$FF	;OUTER CONSTANT
0312	A0 FF	LOOP2:	LDY #$FF	;INNER CONSTANT
0314	88	LOOP3:	DEY	;INNER COUNTDOWN
0315	D0 FD		BNE LOOP3	;LOOP UNTIL ZERO
0317	CA		DEX	;OUTER COUNTDOWN
0318	D0 F8		BNE LOOP2	;LOOP UNTIL ZERO
031A	60		RTS	;RETURN
		;		
0320	00	COUNT:	[long delay count hold location]	
			END	

setting it to a desired value "n" before calling LDELAY to give a total delay of n/4 sec. Finer control over the delay interval can be achieved by reducing the loop counts for the outer and inner loops within SDELAY (0311H and 0313H, respectively) from their original FF value.

The comments in the listing describe the action commands sent to the ET-2 at each step. This program makes use of the one-motor turn shown in Figure 4 (which may not be suitable for all surfaces). Since the outputs of the 6522 hold the values last set until the next output operation, the motor(s) will remain on (or off) during the call to LDELAY. The program has been simplified by using the default delay constant, 2, in the LDELAY loop. With just the right motor on, the robot will turn roughly 45° in the resulting interval, resulting in the approximate octagon pattern (Figure 5). Note that, as mentioned earlier, a power-off interval is commanded after each movement to minimize strain on the drive system (although it is not essential for a one-motor turn).

After the hex code in Table 4 is keyed into RAM at the locations give, the following steps should be followed to start the movement:

Step 1: Check the program carefully against the listing to verify each location. The single step (SST) button may be used to verify proper program execution (although stepping through the delay subroutines will prove tedious). Make sure that both the motor (1302H) and relay(1303H) output ports have been set to 03 (OFF). The motor switch may now be turned ON. Nothing should happen yet.

Step 2: Set the address to 0200, the start of the polygon program.

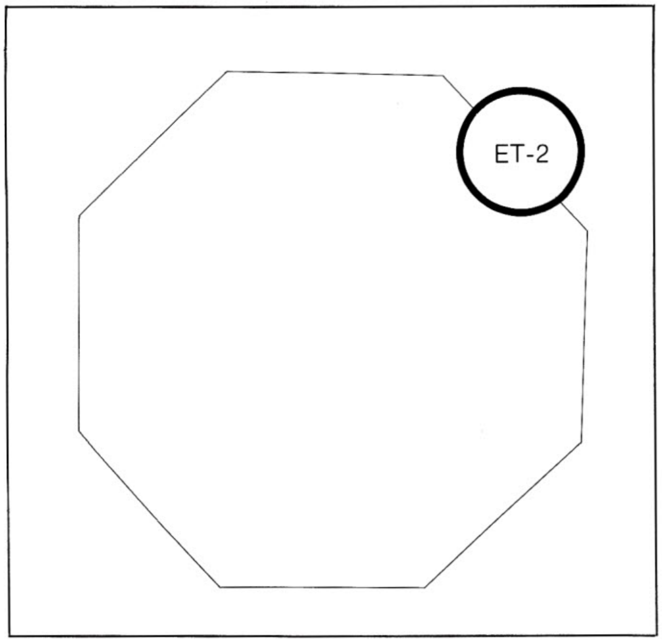


Figure 5. The (approximate) path resulting from the program.

Step 3: Press the GO button. The robot will begin to traverse an octagon.

Step 4: To stop the program, press the ST key and turn the motor switch off.

Stopping the program is best done during one of the pauses, when both motors are off. If the ST key is pressed while a motor is running, it (they) will remain running, due to the latching action of the 6522/6530.

Conclusions and Future Work

A more elegant method of obtaining the program delay would be to make use of the interval timer in the 6522. The device may be set to count up to 256 prescaled clock pulses by writing to the counter address. Based on the write address used to load the counter, the system clock will be divided by 1, 8, 64, or 1024 to produce the prescaled clock pulses. The unit will begin to count down at the prescaled rate as soon as a value is loaded. The register may be read by a program at any time to obtain the current count, and it may optionally be told to generate an interrupt upon reaching zero. Also, each 6522 has two 16-bit programmable counters, but these lack the ability to scale the count rate.

The SUPERKIM controlled ET-2 robot is an excellent, moderately priced system to which the robotics experimenter can easily add more sensors and other equipment. More elaborate systems may make use of the computer's versatile interrupt handling capabilities to design an event-driven real-time control system for the robot. Programs can also be written to use the 6522/6530 I/O ports for A-to-D conversion and interfacing the ET-2's

contact sensors.

In the configuration described here, the computer controlled ET-2 falls short of the definition of a true robot, since all of its movements are "open loop." It has no sensors to tell it that a successful 45° turn has been made or even if it is travelling straight. Until the contact sensors furnished with the ET-2 are interfaced, even simple obstacle avoidance behavior is impossible. Part 2 of this article will describe the addition of sensors and interfaces to enable much more interesting behavior. A good source of additional 6502 machine language programs can be found in Tod Loofburrow's book. [4] These programs, with minor modifications, can be used for controlling the ET-2 with the SUPERKIM.

The ET-2 robot shell is well-built and reliable. The only problem I could find is that it has a tendency to tip over when being driven backwards at full speed with the rear caster in certain positions. Lour points this out and recommends that backing be avoided by doing a 180° on-axis turn instead. The unit can be driven over thick pile carpets without loss of traction, a task which many home robots find troublesome. Each motor draws around nine amps at full speed, so that the system needs recharging after an hour or so of continued use. Lour offers the unit in plan, kit, or assembled form.

References

[1] "KIM-1 User Manual," MOS Technology, 950 Rittishouse Road, Norristown, PA 19401 (August 1976).

[2] "Instructions for SUPERKIM," Microproducts, 2107 Artesia Blvd., Redondo Beach, CA 90278.

[3] "ET-2 Assembly Manual," Lour Control, 1822 Largo Court, Schaumberger, IL 60194.

[4] Tod Loofborrow, *How to Build a Computer Controlled Robot*, Hayden Books, Rochelle Park, New Jersey (1979).

NEW PRODUCTS

Machine Vision from Machine Intelligence Corp.

Machine Intelligence Corp. has introduced the VS-100—a complete vision system for sorting, measuring and computing quality-control data, as well as a vision-controlled interface to electromechanical devices of all kinds.

The VS-100 is cost-effective even for many one-shift applications, where ancilliary equipment is not needed. The system also can be used to assess the feasibility of applying vision in many new applications.

Basic components include a solid-state camera, graphics monitor, operator light pen, Digital Equipment Corp. LSI-11 microcomputer and cassette loader.

The system is easily expandable through standard input/output interfaces that will accommodate external sensors, sophisticated robots and other electromechanical devices. Interaction is direct—through use of a light pen and monitor interface—with all feature selection, machine training and system control implemented through easy-to-follow menu selection. No keyboard entry is needed for basic operation.

Information: Machine Intelligence Corp., 999 Independence Ave., Building F-11, Mountain View, CA 94043. (415) 968-4008.

Circle 7

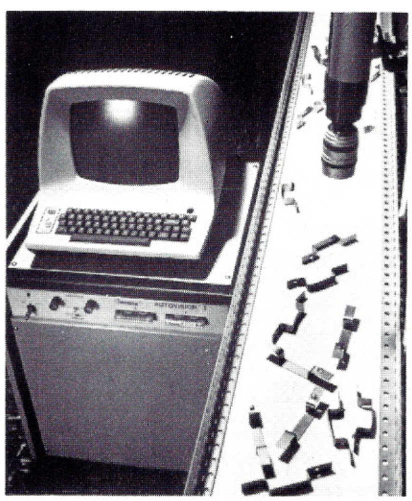
Automatix Autovision System Arrives

Automatix Inc. has announced the off-the-shelf availability of Autovision 1, a new programmable vision-based system for inspection of manufactured parts.

Features include a solid-state camera, video processor, dedicated 32-bit control processor with 160K bytes of solid-state memory, PASCAL-language software, interactive user terminal, industrial-grade system packaging and opto-isolated industrial input/output. The system allows "training by showing" and user-specified extraction of object features.

Autovision 1 is the first product offered by Automatix and will be incorporated in a series of robotics products to be introduced later this year.

Automatix systems can be instructed to detect and identify parts and to measure orientation, area, perimeter, number of holes, hole areas and other part characteristics. These basic characteristics can be used to test part completeness, execute go/no-go decisions and calculate process control variables.

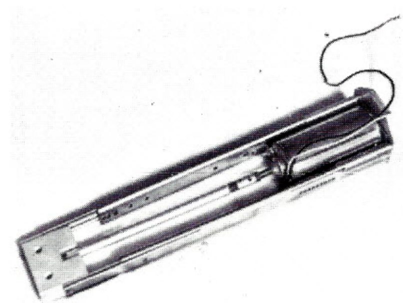


The systems can compute statistical analyses, sort objects and provide information for robotics part handling under the control of the standard Automatix hardware or user-supplied code. System action can then reject or accept the parts, adjust the process or perform other user-specified functions, all in real time.

Information: Automatix Inc., 217 Middlesex Turnpike, Burlington, MA 01803. (617) 273-4340.

Circle 8

The AU-II from Hobby Robotics

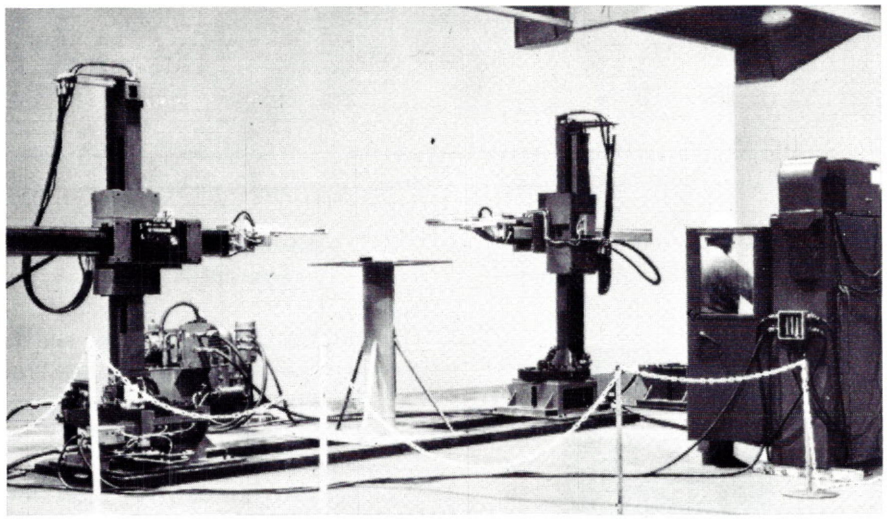


Hobby Robotics Co., a Lilburn, GA., based frim has recently announced completion of development of their first Robot Arm Manipulator Unit. The AU-II is a lightweight, very rugged Lateral Positioning Arm, or Forearm. The AU-II is driven by one powerful P.M. 6-12 VDC Motor, which generates in excess of its rated 15 pounds thrust and retractive force. The Unit has sturdy end-effector mounting plate and shoulder attachment plate, and can be easily covered using standard dryer hose. The AU-II is approx. 18″ retracted, and extends to over 30″ within 4 seconds under no load. The unit is controlled by a linear actuated potentiomenter. This unit will soon be followed by a Hand Unit (end effector) and Shoulder (lift) Unit (presently under development). The

AU-II is priced at $149.95 plus shipping and handling (UPS). Unit is now available. A complete line of supporting components accessories and controls is presently being added. Free catalog and descriptive information can be obtained by writing: Hobby Robotics Co., P. O. Box 997, Lilburn, GA 30247. Circle 10

Software Driven Interface from Micro Computer

The Micro Commander is a software driven interface between your micro computer and the BSR X-10 system. It provides you with an easy and inexpensive way to remote control lights and appliances (motors, TV, stereo, heaters, alarms, fans, pumps, etc.) in your home or office with your micro computer. Because the Micro Commander is a direct interface to the AC power line you do not need to purchase the BSR Command console. You can have direct computer control of up to 256 separate lights and appliances. No wires to run...Easy to use...Think of the possibilities...Comes assembled and tested with 90 day warranty, 14K TRS-80 BASIC program is available on disk or tape (please specify) for an additional $10.00. For more information contact Interface Technology, P. O. Box 383, Des Plaines, IL. (312) 297-2265. Circle 11



Two-Armed Systems: Versatrans in Tandem

Versatran Model FB robots, manufactured by Prab Conveyors Inc., are working in tandem in numerous applications as single robots with two arms.

The result: systems that operate at a significantly increased speed compared to the conventional one-arm approach, in addition to cutting costs and simplifying operations.

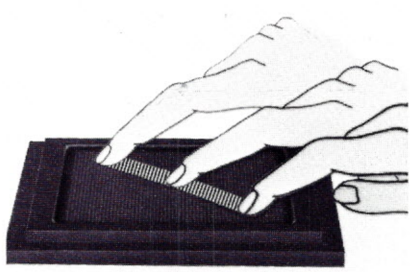
Now installed in a customer plant, one Prab two-armed robot system loads and unloads heavy-duty, 150-pound aluminum forgings. As blanks are delivered by conveyor to an input station near the press, one robot places a blank in the forging die. The other removes the part after the cycle is complete and deposits it on an outbound conveyor.

Horizontal, vertical and swing movements of the two Versatrans are coordinated so neither robot must wait while the other completes its programmed moves. The point-to-point control of the Prab Model 600 microcomputer reduces the overall time cycle, prevents any chance of interference and minimizes interfacing requirements.

The Model 600 has a memory capacity of more than 4,000 points and can store up to 64 independent programs. It can control up to seven axes of simultaneous motion, although, in the two-armed system, each robot uses three axes.

From Prab Conveyors Inc., 5944 E. Kilgore Rd., Kalamazoo, MI 49003. (616) 349-8761. Circle 9

X-Y Controller from TASA



A solid-state alternative to trackballs, thumbwheels, light pens and joysticks is now available from Touch Activated Switch Arrays Inc.

TASA's new X-Y controller produces positioning signals when the user's finger is moved across the device's surface. The user slides a fingertip across the surface in the direction in which positioning or repositioning is desired. The result: X and Y output signals for use in position control.

Applied to computer graphics systems, the controller could provide smooth and accurate real-time X-Y positioning and freehand graphics, drawing, tracing and tracking on a CRT display.

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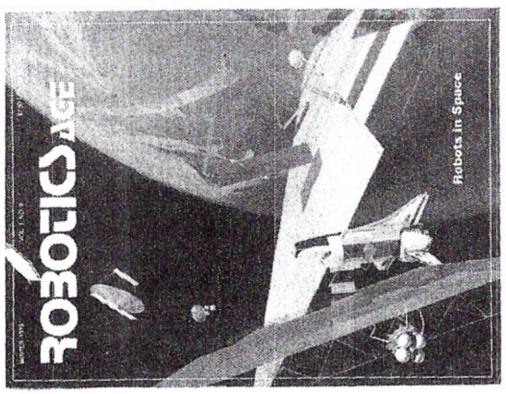

Vol. 1, No. 2
Winter 1979

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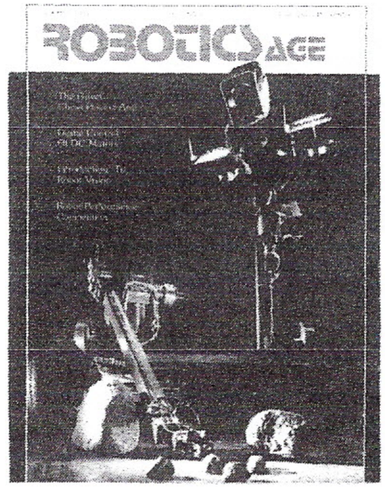

Vol. 1, No. 1, Summer 1979

Due to the overwhelming demand for ROBOTICS AGE, the first printing of our Summer 1979 issue has quickly sold out. However, we are able to offer a limited number of copies for distribution.

- The *Collector's Edition*—The first 200 copies from the first press run have been individually numbered and signed by both the Editorial Director and the Publisher. These registered copies are available for \$20.00, plus \$1.50 for first-class postage and handling. (First issues of other popular magazines have often become worth hundreds of dollars.)

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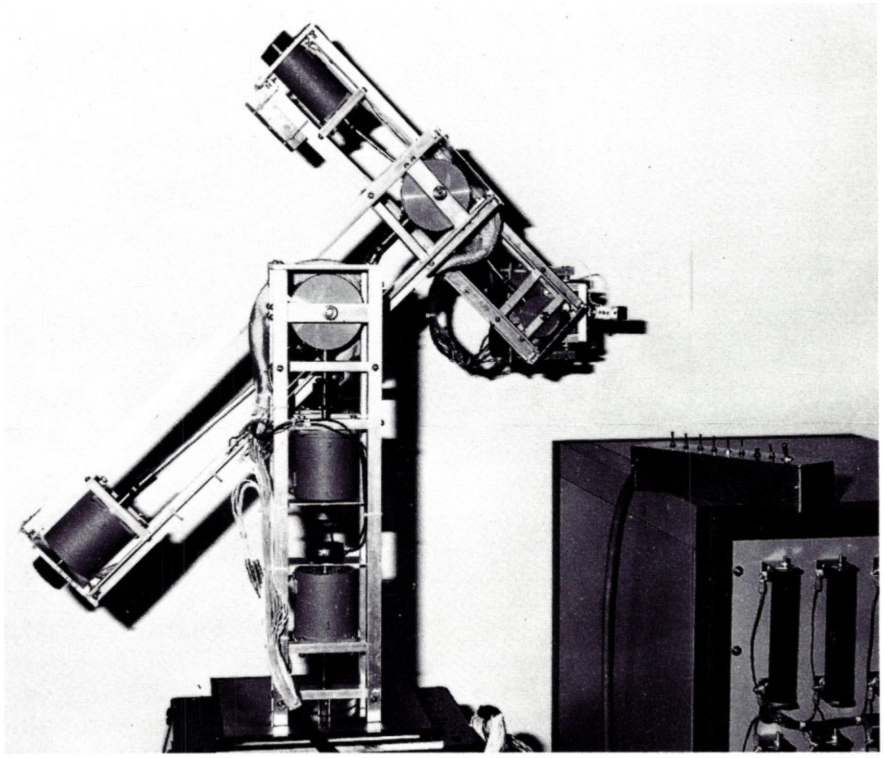
The device can be made rate sensitive with a simple software algorithm. A rapid finger motion (up to 60 inches a second without loss of resolution) would provide large or coarse control; a slow finger motion would give fine control. The positioner's output is TTL and CMOS conpatible, and thus can be easily interfaced with microprocessors and digital computers.

Information: Bob Abler, TASA Inc., 2346 Walsh Ave., Santa Clara, CA 95051. (408) 727-8272.

Circle 12



GRIVET Series-5 Prototype Completed

American Robot Corp. has completed work on the prototype of its GRIVET Series-5 robot, a product aimed at the light industrial market, where payloads weigh less than 5 pounds and speeds are within human range.

Actually, the Series-5 robot will be able to move at twice the average human speed while carrying its maximum payloads. In this sense, the robot could be a direct replacement for a human worker performing the same tasks.

The company expects to have the robot in production by Christmas, according to company President John K. Gallaher, Jr.

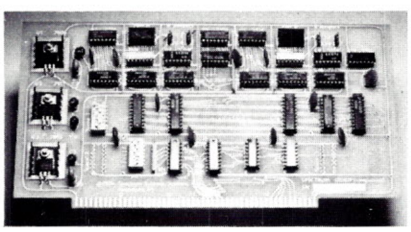
Available with several standard features, the production model will sell for $10,000.

From American Robot Corp., PO Box 10767, Winston-Salem, NC 27108. (919) 748-8761.

Circle 14

Dual 12-Bit Buffered Input Ports for the S-100 Bus

The Spectrum D12BIP logic board provides a unique new capability in data acquisition to S-100 bus users. This board has two input ports with 64 bytes of FIFO buffer to allow for data rate mismatches between the source and the processing of data. The board is organized as two external ports of 7, 8, or 12-bits, with non-data bits usable for control. Each external port is accessed as a pair of input ports by the S-100 bus. The FIFO buffers operate at 1 MHz and are strobed by the data source. Applications include a variety of monitoring activities, both digital, or with appropriate converters, analog. Strobed keyboard devices are especially easy to interface. For more information, contact Spectrum Business Systems, 29350 Southfield Rd., Southfield, MI 48076, 313/559-5252.



Circle 13

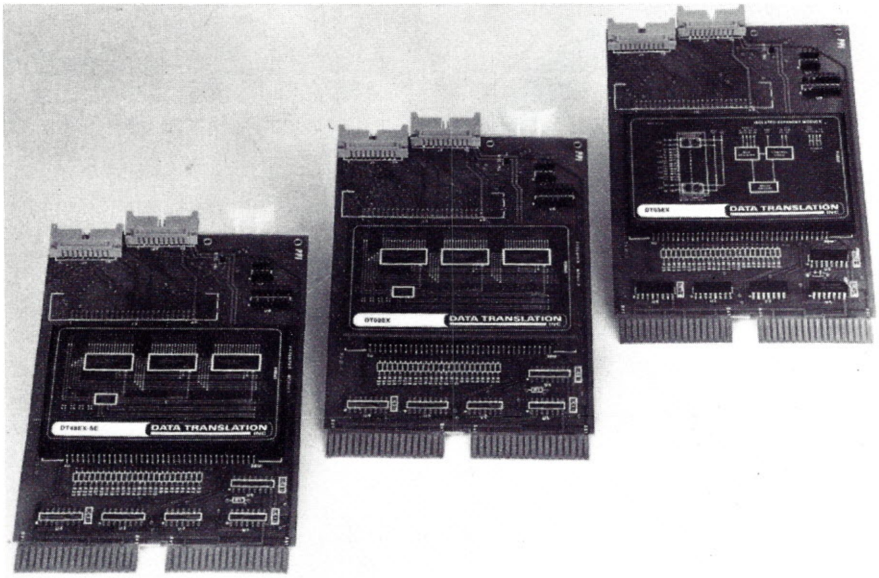
Multi-Channel Analog I/O

Data Translation is offering a new family of 4-channel 8- and 12-bit digital-to-analog converters with fully buffered inputs and a choice of four independent voltage outputs or a like number or independent 4- to 20-milliamp current-loop outputs.

Both the 8-bit Model DT215 and the 12-bit Model DT214 consist of four individual D/A converters, each preceded by its own clocked input data buffer. A common Master Clear line-driven LOW clears all input data buffers. This type of digital buffering minimizes erroneous D/A converter outputs that result from segmented input data and eliminates the voltage-droop penalty suffered by long-term sample-hold storage techniques.

Both models are available standard in LSTTL or optionally in CMOS. Prices range from $335 to $490, depending on output capability and bit capacity chosen.

A trio of dual height-expander boards with full hardware and software compatibility with the Digital Equipment Corp. LSI-11 dual-height Q-Bus backplane is now



available.

They are designed to increase the channel capacity of Data Translation's DT2760 series of dual-height, Q-Bus-compatible analog input systems. A single expander card can extend a 10-channel system to a capability of up to 64 channels. All models are complete with required control logic and "break-before-make" new channel selection for failure-free performance.

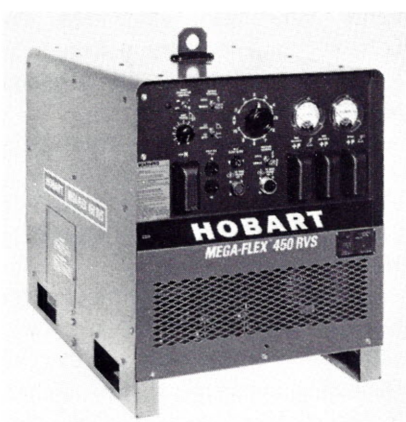
The new boards—DT2772, DT2774 and DT2775—extend, respectively, the DT2762 (high-level input), DT2264 (low-level, wide-range) and DT2765 (flying-capacitor-isolated, low-level, wide-range) analog interface boards.

Complete specifications and price information on the above are available from Data Translation Inc., 4 Strathmore Road, Natick, MA 01760. (617) 655-5300.

Circle 15

New Combination CC/CV 450 AMP Welder

The dual-purpose Mega-Flex 450 is the newest combination CC/CV welding power source from Hobart Brother Company. It offers the same exceptional constant voltage characteristics as the standard



Mega-MIG 450 along with the excellent constant current performance of the Mega-ARC family.

The versatile Mega-FLEX 450 can be used for all constant voltage processes including gas metal-arc (GMAW), flux-cored arc (FCAW) and submerged arc (SAW) welding.

Under the constant voltage mode, the Mega-FLEX 450 features output voltage regulation, solid state contactors, voltage regulation at the arc with remote voltage sensing, local or remote voltage control and single wide-range control.

For constant current processes, the Mega-FLEX 450 features fully closed loop current feedback, output current regulation, adjustable arc characteristics (ARC FORCE CONTROL) and single wide-range current control.

Standard featrues of the Mega-FLEX 450 for both modes include line voltage compensation, solid state components, advanced SCR design, built-in overload protection and volt and amp meters.

The Mega-FLEX 450 is compatible with Hobart's digital wire-feed system.

For more information contact Hobart Brothers Co., 600 W. Main St., Troy, OH 45373.

Circle 16

A/D + D/A Card for Apple II

Mountain Computer Inc. has a new analog-to-digital and digital-to-analog card permitting Apple II computer applications in data acquisition and control.

All functions are carried out on a single printed circuit card that occupies one peripheral slot in the Apple II. Features include 16-channel 8-bit A/D input and D/A output with 9-microsecond conversion time, permitting high-frequency applications not possible with slower cards.

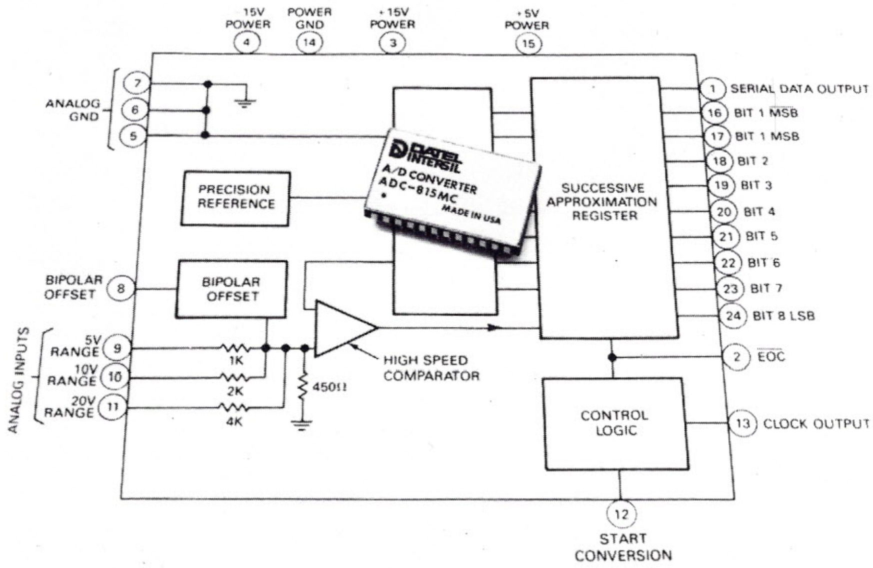
From Mountain Computer Inc., 300 Harvey West Blvd., Santa Cruz, CA 95060. (408) 429-8600.

Circle 17

Data Acquisition Products from Datel-Intersil

Several new products are recent additions to Datel-Intersil's family of data acquisition products.

Among them is the SHM-UH3, an ultrahigh-speed sample hold designed for use with ultrafast analog-to-digital converters with resolutions of up to 10 bits. Its high-speed characteristics make the SHM-UH3 one of the fastest sample holds available as a standard product.



These characteristics include 30-nanosecond acquisition time, 30-picosecond aperture uncertainty time, sample rate of up to 10 megahertz while making full-scale acquisitions, 45-MHz sample mode bandwidth and output slew rate of 500 volts per microsecond. (Price: $230 in quantities of one to nine, stock to four weeks.)

The Model AM-414 is a chopperless, ultralow-drift operational amplifier specifically designed for accurate amplification of low-level signals where low noise and drift and precise closed-loop gain are required.

Typical input offset voltage drift is 0.3 microvolts per degree C., with 2.0 V/°C maximum for Version A and 1.3 V/°C for Versions B and M (military). The op amps could find application in photocells, thermocouples, strain gauges, digital voltmeters, precision integrators, active filters and sample holds. (Price: $7 each for A, $12.95 for B and $22.50 for M, in quantities of one to 24.)

Datel-Intersil has two new 8-bit analog-to-digital converters—the ultrafast ADC-815, which has a 600-nanosecond maximum conversion time, and the high-speed ADC-825, with a 1-microsecond time.

Both are designed for such high-speed applications as pattern recognition, telecommunications systems, fast servosystems, radar systems, computer typesetting, high-speed instrumentation and automatic control systems, and fast data acquisition systems.

In addition to the fast conversion rates, the new models have six pin-programmable input voltage ranges—0 to +5V, 0 to +10V, 0 to +20V, 2.5V, 5V, 5V and 10V—for maximum applications flexibility. Other features: a logic input that switches the converter from unipolar to bipolar operation; output coding in straight binary, offset binary or two's complement; and serial-data, clock and status outputs.

Price: ADC-815, $205; ADC-825, $165, in quantities of one to 24. Availability: eight to 12 weeks.

An eight-page technical brochure by Datel-Intersil details the electrical and mechanical specifications of two 12-bit, 62-pin miniature data acquisition systems—Models HDAS-16 and HDAS-8.

Both are modules suited to low-level signal applications involving amps, transducers, strain gauges and thermocouple interfaces.

For information about any of the above products, write Datel-Intersil Inc., 11 Cabot Blvd., Mansfield, MA 02048, or call (617) 339-9341.

Circle 23

High Power R/C Hobbyist Servos

The Sail Engineering Proportional Control Systems are high power servos designed for use with today's digital radio systems. Each unit has a Kraft-Multicon servo connector enabling direct connection to Kraft equipment. Adapter "pigtails" are available for all radio systems. All components are extra heavy duty for long life and service with solid state electronics throughout. The units have nine inch output arms for sail control in model sailing yachts. A wide range of output arms is available for any use and any amount of movement such as heavy nose wheel steering, heavy retract landing gear mechanisms, large control surfaces on boats and aircraft and these controls now make a new phase of scale modeling possible: STOL type aircraft. All units plug directly into the radio receiver as any other servo would. Output arms secure to the output shaft with a clamping collar that allows easy adjustments or removal of the arm.

Two models are available, the SE-1P: weight 16 ounces, torque 40 lb-in., 135 degree rotation, drawing 80 ma to 1.5 amp under load; and the SE-2P: weight 22 ounces, torque 80 lb-in, 135 degrees rotation, drawing 300 ma to 3 amps under load.

Both are available from Sail Engineering, P. O. Box 8439, Richmond, VA 23226.

Circle 18

Cromemco Z-80 Now Has LISP

LISP—a powerful programming language developed for artificial intelligence applications—is now available for use by Cromemco Inc. Z-80-based computer systems.

The language is used widely in a

number of applications: interactive data base systems, systems that understand natural language, systems for symbolic manipulation of mathematical expressions, intelligent controllers, computer-aided design, design automation.

Cromemco LISP incorporates many advanced features, among them standard control constructs, complete string and character processing, fixed and floating-point arithmetic, property-list functions for constructing data bases, interface capability with non-LISP procedures and a comprehensive library of more than 150 utility functions. An "autoload" feature allows infrequently used functions and symbols to be stored on disk, making larger user programs possible.

Five-inch and 8-inch floppy diskettes are available from Cromemco Inc., 280 Bernardo Ave., Mountain View, CA 94043. (415) 964-7400.

Circle 19

Industrial Robotics Consulting Service

Christian and Timbers, Inc., is a newly formed company offering consulting and recruitment services in industrial automation and high technology, including robotics, machine and tool design, electronics, interactive graphics, and CAD/CAM.

Services include feasibility, application and marketing studies, proposal preparation, and technology assessment studies, as well as system design, engineering, and documentation. The firm will assist clients in increasing productivity through the cost-effective application of robots and automation technology.

Contact: Jeff Christian, Christian and Timbers, Consulting and Recruiting Specialists, 26949 Chagrin Blvd., Ste. 100, Cleveland, OH 44122. 216/464-8710.

Circle 20

Moog Describes Repair Service

In an eight-page brochure, Moog Inc. Industrial Division describes the newly organized factory repair service for its complete line of electrohydraulic products and electronic control components.

The expanded service includes a fully equipped repair department, a stock of replacement parts and systems to handle returned units and shipment of popular models from stock.

Moog manufactures servovalves, servoactuators, servodrives, proportional valves, hydrostatic transmission pump strokers, servoelectronics, programmers, tranducers, radio controllers and other products.

Send for Brochure No. 340 780. available from Moog Inc. Industrial Division, East Aurora, NY 14052. (716) 652-2000.

Circle 21

MEDIA SENSORS

Robots are attracting more attention in the media. TV, radio, newspapers, and magazines have enthusiastically climbed aboard the bandwagon and are trumpeting the arrival of America's answer to its productivity problems. Robots, those marvelous machines with cameras for eyes, computers for brains and hands of steel will lead the parade of advanced technologies marching America to the green fields of "Reindustrialization". *Omni, Next, Discovery, US News, Business Week, Fortune, Iron Age*, even *Readers Digest* have recently run articles, and many major newspapers, TV and radio stations have done reports on robots. Why this surge of interest in a twenty year old struggling technology?

"Productivity," a new buzz word for the 80's is rapidly replacing the old buzz words "Return on Investment" and "Profit Centers". During the last three decades US Industry has painfully lagged behind its foreign competitors in expenditures for R & D, new plants and equipment, and is now waist-deep in a quagmire of obsolete manufacturing machines and methods. It took years to maneuver ourselves into this precarious position and these patterns of productivity are not quickly or easily reversed. Grasping for quick-fixes to pull ourselves free from our past mistakes only further endangers our economic wellbeing.

Robots and other intelligent machines will certainly help improve America's productivity. But, these are only tools and will play a limited role in our recovery. The future depends on how well we apply these new tools. Many changes are needed on the manufacturing floor before computers and robots can be successfully integrated into our industrial processes.

Obviously, an increase in interest in advanced manufacturing tools is beneficial, and articles in *Fortune* and *Business Week* have brought this message an important new audience: top management. Plant engineers have long recognized the value of NC/CNC machine tools and CAD/CAM, but robotics technologists have had a hard time selling their ideas to profit-minded managers looking for a quick return on investment. Because of all the recent attention in the business media the situation is now nearly reversed, with agressive productivity-minded management pushing engineers to introduce these new tools into the manufacturing process—and therein lies the rub.

Most of our manufacturing methods are dependent upon and structured for manual operations. The Japanese have been preparing for automation for years and are in a superior position to use the new tools. It has been their plan to make long range committments to automation, not to get rich quick, but to get rich and stay rich. Before the U.S. can really start on the road to reindustrialization it must first address itself to structuring the manufacturing environment in ways that will take advantage of the new methods and machines. The future belongs to the intelligent. Those businesses and industries that learn how to best apply these powerful new tools will grow and profit.

We are pleased that robots have been getting so much attention in the press, and believe that this attention will help speed the introduction of robots to the manufacturing floor. It is our hope that management will make a serious long-term investment of time, talent, techniques and capital to assure the successful application of robots and other intelligent machines.

Below are summaries of some of the recent articles that have appeared about robots.

US News & World Report, Sept 22, 1980, **Rebuilding America, It Will Cost Trillions**. Growing concern over the creaking economy has triggered searches for a way to remake the industrial base of the country. Productivity gains have been below those of US competitors. One way to boost productivity is through increased research. The Commerce Dept. on Sept 4 announced it will set up a center to develop advanced automated robot welding. Peter F. Drucker of the Claremont Graduate School says that to regain its competitive edge against low-wage labor forces in other countries the US must encourage a fairly rapid shrinkage of blue-collar employment. Future competitive plants would operate with computer-controlled robots. Workers would program computers rather than operating machines.

TIME, Sept. 8, 1980, **Detroit's Uphill Battle**. Of the 56 American auto makers of 1925 only 4 remain and two of these, Chrysler and American Motors, are in danger of failure. The auto industry has been through slumps before but this year's is unique since it could leave the industry permanently weakened. Designing and producing fuel-efficient cars will take 3 years and cost $80 billion. Detroit is not just turning out new models but is also trying innovative ways to build them. Henry Ford would never recognize the new assembly lines. Industrial robots are taking over many tasks formerly done by workmen. A robot costs $6/hr. as compared to $17/hr. for an assembly-line worker. Programmed by computer, the robots can lift and wield welding torches with precision that is better-than-human. Chrysler's K-cars are 98% machine welded. GM robots under development will be capable of selecting parts from a bin, checking for defects and using them only if perfect.

Discover, October 1980, **Robot Joy Stick**. Ken Salisbury, a graduate student at Stanford University, has invented a joystick controller that earthbound scientists can use to guide the movement of the Space Shuttle's robot arm. It is somewhat like a sophisticated version of the control wheel found on airplanes. The operator can literally feel the forces acting on the distant arm. Forces on the robot arm are sensed, converted to digital data, and radioed back. The incoming signals control electric motors to create forces that the human operator can feel.

Popular Science, June 1980, **New Workers on the Assembly Line: Robots That Think**. The eerie scene of "intelligent" machines going independently about their business is repeated thousands of times daily at Ford, GM, and Chrysler plants in the US and is even more common in Japan. A new generation of robots is exploding onto the industrial scene. "Industrial robotics used to be more like automation," said GM's Ed Kavetsky, "The machines just repeated the same motions. But now we're using general-purpose digital computers to get true robotics." The best of the newest robots can see, touch, and make intelligent decisions. (Numerous applications are listed.) One of the most advanced industrial applications is under development at Westinghouse Electric, where a robotic batch-manufacturing assembly line will produce fractional horsepower electric motors. This is significant since batch manufacturing makes up about 75 percent of US manufacturing. More than half of all robots sold are made by Unimation Inc. Unimation has been making robots for 20 years. Their original units were controlled by paper tape.

The real advance in modern robots is the PUMA. One of the first of these is being used by GM as part of a robot vision system. The system uses two bright lights angled down through lenses to form a brilliant line across the conveyor belt. A video camera looks down at the line, sensing objects moving along the belt. GM has already installed dozens of PUMA's in their plants. "Robots are ideal for light assembly operations,'' says Walter Cwycyshyn of GM. The robots' computer software "is extremely complex," says Brian Carlisle, "Each

joint goes through a coordinate transformation ending up with six four-by-four matrices to be solved. The LSI-11 outputs a new point every 29 microseconds, and at the same time, internal microprocessors are doing 32 recomputes on the motion." The result is pinpoint accuracy.

Fortune Magazine. December 17, 1979. **"Those Smart Young Robots on The Production Line,"** by Gene Bylinsky. Also reprinted in April 1980 Reader Digest.

Fortune magazine began their series on "The State of American Innovation" with an article about the new generation of robots and robotic devices. Claiming the new sophisticated computer-controlled robots to be "the latest form of automation" and a "technology in which the US is in the forefront of innovation". The Japanese may use robots more extensively than the rest of the world because they are a labor-short country, but the newest and most sophisticated American robots out-perform their overseas cousins.

A general discussion of the many industries now using robots and descriptions of various kinds of applications is given, along with speculation by those in the industry as to what robots will be doing in the near future. Work being done by the National Science Foundation and the National Bureau of Standards is credited with helping lead the way to advanced robotics and sensory feedback systems.

Fortune magazine concluded its rather optimistic portrait of the robotics industry with the conservatve estimate of only 5% of the western world's blue-collar work force being replaced with robots by the end of the century.

Business Week June 9, 1980 **"Robots Join the Labor Force."** This article looks at the business of robotics, both from a builder's and a user's standpoint. Some of the ramifications of the apparent upcoming robot boom and what it will mean to American industry and labor are explored. Dramatic reduction in the cost of robots is projected if some of the top computer companies such as: Digital Equipment, IBM and Texas Instruments jump into the robot market.

The Japanese threat of continued development and implementation of advanced robotics, because of joint government and industry efforts, is worrying American manufacturers, the article points out. US industry is responding by investing in more sophisticated automation such as CAD/CAM (comp. aided design/ comp aided manufacturing) and vision techniques to lead the batch manufacturing hurdles, hoping to catch up in the race for increased productivity.

Media Sensors *are brief summaries of robotics-related items that have appeared in the mass media. An attempt is made to paraphase the content of the original item without altering its tone. The views expressed in these items are not necessarily those of ROBOTICS AGE. The first contributor of any clipping selected will receive $10 for its use.*

LETTERS

Dear Editor,

I would like to make some comments about Elaine Rich's review of my book "Principles of Artificial Intelligence" appearing in the previous issue. Artificial Intelligence (AI) research has both scientific and engineering goals. As science, AI aspires to explain the nature of intelligence, natural or synthetic. As engineering, AI aspires to design and build artifacts with sophisticated perceptual and reasoning skills. My book treats primarily the engineering aspects of AI. There is nothing particularly special about AI as contrasted with other engineering disciplines, except that we really haven't gotten very far with AI yet (as compared with, say civil engineering). Thus what appears to Rich (at this early stage) as a "two-headed monster" is really the beginnings of the standard sort of spectrum between theory and practice in any engineering discipline. When a civil engineer designs a bridge, say (s)he applies much "art," uses a great deal of previous experience, and also needs to be aware of a number of theoretical ideas. Civil engineers are taught about many of these theoretical ideas (statics, dynamics, the nature of stress, etc.) early on. These are "weak ideas" in the sense that they are applicable in a number of situations (bridges, buildings, highways, etc.), and need to be supplemented in particular cases by detailed specialized knowledge. I don't think the situation is very different in AI. People who are going to specialize in the engineering discipline of building smart systems probably ought to have been enculturated with a bit of general knowledge and theory about search, unification, the predicate calculus, etc. These concepts provide a setting, foundation, and vocabulary for more specific and practical ideas. My book ought to be viewed as an attempt to provide for AI what a course in fundamental statics and dynamics provides for civil engineers. One can't read it and then rush out and build systems. Rich makes the point that one might get more out of the book after having some courses on some actual AI systems. Well, I don't know. My guess is that the book ought to be used in early courses on AI to provide foundation ideas.

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Erratum

In the Summer 1980 issue of *Robotics Age*, in the "Letters" section on page 2, the equation for ideal PID control (2nd column, top) contains an error: the derivative correction term should read "$-K_d\dot{w}$" instead of "$-K_d w$" as originally shown.

We would also like to mention that the article "Industrial Robots: Today and Tomorrow," by *Robotics Age* Industrial Editor Jerry Saveriano, is an adaptation of a paper presented to the Society of Photo-Optical Instrumentation Engineers (SPIE), Feb. 1979 Conference.

ORGANIZATIONS

Prab Moves Into Europe

Prab Conveyors Inc., of Kalamazoo, MI, has ventured across the Atlantic to form a new company that will handle the sale, installation and servicing of Prab robot products throughout Western Europe.

The new company, Prab Industrie Roboter GmbH, is located in West Germany. Larry Beam, former international marketing manager for Unimation Inc. has joined Prab as the managing director of the European operation.

This first Prab venture outside the United States will be followed by the formation of similar companies in France, Scandinavia, the United Kingdom and the Mediterranean.

Prab President John J. Wallace said, "We've chosen Germany as our first site because of its highly developed industrial base, strong currency and very active robot market."

Meanwhile in the U.S., Prab has completed the move of the high-technology Versatran robot line to its Kalamazoo site. Prab purchased the line last year from AMF Inc., of Herndon, VA.

The Versatrans, manufactured by AMF from 1958 to 1978, include four models that can handle materials and equipment weighing 100 to 2,000 pounds. The robots are available with upright and overhead traversing bases, as well as overhead mounting configurations.

Several key engineers and manufacturing and service personnel joined the Versatran move to Kalamazoo and assisted in what was called a smooth transition. They now serve in similar positions at Prab.

IGES Makes CAD/CAM Exchanges Possible

The Computer and Automated Systems Association of the Society of Manufacturing Engineers has officially endorsed National Bureau of Standards efforts to develop a specification facilitating the exchange of graphic and geometric information from one Computer-Aided Design/Computer-Aided Manufacturing system to another.

The Initial Graphic Exchange Specification makes such exchanges possible and can store data found in CAD/CAM systems. A key feature of IGES is that graphics users are not limited to one graphics system, the association said.

As the field of computer technology advanced, the lack of a data exchange method was seen as the major problem in realizing the technology's full potential. With IGES, users can develop codes to translate data between their systems and IGES.

According to the recent Delphi Forecast on CAM conducted by SME and the University of Michigan, one-quarter of all U.S. manufacturers will have integrated CAM with CAD by 1990. Computer graphics will then be used for both product and tool design.

For more information or for copies of the specification, write Dr. Roger Nagel, National Bureau of Standards, Building 220, Room A123, Washington, DC 20234.

IGES capabilities will be demonstrated at SME's Autofact West conference and exposition Nov. 17-20 in Anaheim, CA. For information, write or call Kevin Miller, SME, 1 SME Drive, PO Box 930, Dearborn, MI 48128. (313) 271-1500, Ext. 367.

Calendar

Work Measurement Techniques
Sept. 22-26
Hershey, PA

Up-to-date concepts in fundamental work measurement techniques will be discussed in five one-day workshops sponsored by the American Institute of Industrial Engineers.

The courses are designed for industrial engineers, methods analysts, work measurement analysts, time study engineers and industrial engineer technicians. Registrants may attend any or all of the workshops: operator performance rating, methods improvement and cost reduction, time study fundamentals, predetermined time standards and construction of standard data and time formulas.

Fees will be $95 a day for AIIE members and $105 for non-members, or $425 and $475, respectively, for the the full week.

Details are available from AIIE, 25 Technology Park/Atlanta, Norcross, GA 30092. (404) 237-8202.

Military & Space Robotics
Nov. 3-5

Washington, DC

Applications of robotics to military and space work will be the focus of a conference sponsored by the Naval Research Laboratory.

The conference will present a look at current and future applications and at advanced robot technology: sensors, object recognition, control systems, high-level robot languages, robot planning, problem-solving systems. Explicitly excluded: industrial robots with little or no sensing capabilities.

For information, write or call Dr. James R. Slagle, Computer Science Laboratory, Code 7507, Naval Research Laboratory, Washington, DC 20375. (202) 767-3850.

Autofact West
Nov. 17-20
Anaheim, CA

The Society of Manufacturing Engineers has announced additional details about Autofact West, its first West Coast conference and exposition on the automated, integrated factory.

Seven component programs will make up Autofact West, including a conference devoted to robotics. The others: Assemblex VII, CAD/CAM VIII, Predictive Maintenance II, Materials Flow II, Qualinspex II and the Pacific Electronics Manufacturing Conference.

The format, though expanded, will resemble the Autofact I and II programs sponsored by SME in Detroit in fall 1977 and 1979.

Forty-six technical sessions have been announced. The robotics conference will include sessions on robots in aerospace, increasing productivity using robots, advanced robotics systems and robots in assembly.

For details about the conference, exhibits, registration and hotel accommodations, write Autofact West, SME Public Relations, 1 SME Drive, P O Box 930, Dearborn, MI 48128.

SME Conferences & Clinics
Fall 1980 to Summer 1981

Six robotics programs will be among 139 conferences, clinics and tool shows to be presented by the SME in the coming year.

Literature describing program content and registration procedures will be available two months before each event. Write to SME, 1 SME Drive, P O Box 930, Dearborn, MI 48128, or call (313) 271-1500. Specify the Special Programs Department for programs labeled (SP) below, the Expositions Department for those labeled (EX). The schedule: Oct. 28-30, Robots V Conference and Exposition (EX), Dearborn, MI; Dec. 2-4, Robots: Management Overview Clinic (SP), Marco Island, FL; Feb. 3-5, Robots: Management Overview Clinic (SP), Houston; Feb. 24-26, Robots Clinic (SP), Oakland, CA; June 2-4, Robots Clinic (SP), Cleveland; June 16-18, Robots Clinic (SP), Denver.

RoViSeC, the First International Conference of Robot Vision and Sensory Controls
April 1-3, 1981
Stratford-upon-Avon, U.K.

RoViSeC aims to integrate industrial needs and research solutions. Presentation topics include: vision systems, optical recognition, imaging systems, sensor design, vision software, tactile sensing, voice communication, and industrial applications. Organized by: IFS Ltd., 35-39 High St., Kempston, Bedford, MK42 7BT England.

Seventh International Joint Conference on Artificial Intelligence
August 24-28, 1981
Vancouver, BC, Canada

Submission categories include: AI applications, natural language, vision, problem solving, cognitive science, export systems, AI theory, knowledge acquisition and representation. Submission date: March 1, 1981. For details contact: Pat Hayes, General Chairman IJCAI Pat Hayes, General Chairman IJCAI-81, Univ. of Rochester, Dept. of Computer Science, Rochester, NY 14627.

IEEE Computer Society Conference on Pattern Recognition and Image Processing
August 3-5, 1981
Hyatt Regency Hotel, Dallas, TX

Papers are sought on all aspects of image processing and PR. Submission date: January 15, 1981. Details—Azriel Rosenfeld, Computer Science Dept., Univ. of Maryland, College Park, MD 20742.

Robots in Australia: A New Era for Industry

A day-long seminar on the role of robots in Australian industry will be on October 29, 1980.

Titled "Intelligent Machines at Work," the seminar is sponsored by Productivity Promotion Council of Australia and the Institute of Industrial Engineers. It will be held at the Hyatt Kingsgate, Sydney.

For further information contact Susan Hope or Gordon Seeto, Productivity Promotion Council of Australia, PO Box J157, Brickfield Hill, Sydney 2000. PH: (02) 218-8271 or 218-8257.

CLASSIFIED

Our classifed advertising section is for readers wishing to buy, sell or trade hardware or software. The price is 30¢ per word. The first word is set in all caps. Minimum 20 words. Send copy with check to ROBOTICS AGE CLASSIFIED, P.O. Box 801, La Canada, CA 91011.

02-1045-2 Pattern Recognition (Bongard). Primarily for specialists in computers and artificial intelligence, this book uses a nonmathematical approach. For everyone attempting to understand such brain functions as the ability to find similarity, create abstract ideas, and act by intuition. The Soviet scientist clarifies the meaning of pattern recognition and problem solving. 256 pgs. $17.00 including shipping. SDG Research, 3947 Delta, Rosemead, CA 91770.

BOOKS About Robotics and Artificial Intelligence. Send stamp for our descriptive catalog. Robotic Publishing, 17095 Bridgeport Rd., Dallas, OR 97338.

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